Universidad Carlos III de Madrid

TESIS DOCTORAL

Design, Development and Evaluation of a Robotic Platform for Gait Rehabilitation and Training in Patients with Cerebral Palsy

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Cristina Bayón Calderón

Marzo 2018

A mi familia

A Carlos

You can do anything if you set goals. You just have to push yourself.

-RJ Mitte-

No es que no quiera, es que no quiero querer.

-Joaquín Sabina-

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No tengo palabras para describir todo lo que he sentido en estos cuatro años y lo mucho que ha significado para mí el desarrollo de esta tesis doctoral. Hay tanta gente detrás de este trabajo, que casi me parece imposible poder nombrarlos a todos.

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To the ones that left the group before me, thank you for making a mark on my life: Bea, thank you for your support listening to me. Rafa, you are the best person I have ever met; I am very lucky to have you as my friend. Óscar, you know that half of this thesis is yours; it was a pleasure to carry out this job with you.

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Finally, but most importantly, I would like to recognize my “Maestro”. Eduardo, from the first day we had a special connection that made everything go as it did. Thank you for taking a chance with me in this unforgettable experience. Only you know all that I have felt, you have been with me for the best and the worst moments, always managing to make me smile. I have learned a lot from you, and thanks to your personality and your effort, the Lab continues working successfully. Whatever happens in the future, I will never forget you.

Resumen

La Parálisis Cerebral (PC) es un conjunto de alteraciones neurológicas debidas a una lesión cerebral surgida en la infancia, que afectan de forma permanente al movimiento de la persona y a su coordinación motora. En algunos casos, estas limitaciones pueden ir acompañadas de problemas sensoriales o intelectuales, dependiendo de la severidad de la lesión. Es la discapacidad física más común en pacientes pediátricos, con una prevalencia de 2.11 casos por 1000 nacimientos. Los tratamientos convencionales de la PC pueden dividirse en tres pilares principales (fisioterapia, terapia ocupacional y logopedia), los cuales deben progresar cada día en busca de ofrecer mejores resultados a los pacientes.

Como parte de la mejora de estos tratamientos convencionales, la terapia por asistencia robótica de la marcha es un concepto que ha surgido en los últimos años para complementar la terapia física convencional de personas con problemas motores, como aquellos derivados de la PC. Sin embargo, el uso de entrenadores robóticos está aún limitado en la práctica clínica: los clínicos y familiares demandan más investigaciones que confirmen la efectividad de la terapia robótica, así como estudios que determinen si la rehabilitación robótica realmente merece la pena.

El objetivo principal de esta tesis doctoral es ofrecer una novedosa solución robótica para la rehabilitación de la marcha de pacientes pediátricos con PC y desórdenes similares. El enfoque que se pretende dar con el dispositivo robótico propuesto en la tesis es distinto al que existe hasta el momento, aportando nuevas ideas no sólo sobre el diseño y el control del dispositivo, sino también sobre los protocolos de intervención clínica. La metodología utilizada para alcanzar este objetivo se basó en un estudio detallado sobre la aplicación de entrenadores robóticos de rehabilitación elaborados en los últimos años. Con esta investigación se identificaron las principales limitaciones y desafíos de las terapias robóticas actuales, los cuales sirvieron para sentar las bases del diseño y desarrollo de una nueva plataforma robótica englobada en el marco de trabajo de esta tesis: CPWalker.

CPWalker está compuesto por dos partes principales: un andador inteligente y un exoesqueleto con 6 grados de libertad. A través de ellas, es posible proporcionar soporte

parcial de peso del usuario al mismo tiempo que se realiza un movimiento guiado de las articulaciones con desplazamiento en entornos reales.

El entrenador robótico CPWalker promueve la progresión de pacientes con PC dentro del tratamiento de rehabilitación, incrementando el nivel de intensidad y frecuencia de los ejercicios, al mismo tiempo que aumenta la motivación del usuario y adapta la terapia a las posibilidades de cada paciente. Para ello, utiliza estrategias de control innovadoras, las cuales pueden ser seleccionadas de forma individual para cada articulación, dando así una alta versatilidad en la definición de los tratamientos.

La plataforma robótica desarrollada fue evaluada tanto técnica como clínicamente con pacientes pediátricos. Los resultados muestran el potencial del dispositivo como herramienta de rehabilitación, proporcionando también soporte preliminar para futuras implementaciones clínicas, no solo en CPWalker, sino también en otros dispositivos robóticos de la marcha.

El trabajo desarrollado en esta tesis ha sido llevado a cabo con la ayuda financiera del Ministerio de Economía y Competitividad español y la Secretaría de Estado de Investigación, Desarrollo e Innovación, bajo el contrato BES-2013-064225/DPI2012-39133-C03-01.

Abstract

Cerebral Palsy (CP) is a set of neurological disorders derived from a brain lesion occurred in infancy or early childhood, which permanently affect body movement and muscle coordination. In some cases, these limitations go together with sensory or intellectual problems, which depend on the severity of the disease. CP is the most common physical disability in childhood, presenting a prevalence of 2.11 cases per 1000 births. Conventional treatments for CP could be divided in three main pillars (physiotherapy, occupational therapy and speech therapy), which must be continuously improved looking for better results for the patients.

As part of the enrichment of these conventional treatments, robot-assisted gait therapy is a promising tool that has appeared in the last years to complement conventional physical therapy of people with gait disorders as those derived from CP. However, the use of robotic trainers in pediatric clinical practice is still limited: clinicians and families demand further research that confirms the effectiveness of robotic therapy, and clarifies if robotic rehabilitation is worthwhile for their children.

The main objective of this doctoral thesis is to provide a novel robotic solution for gait rehabilitation of pediatric population with CP and related disorders. The approach that the proposed robotic device expects to offer is different from those existing so far, providing new ideas not only about the design and control of the device, but also about clinical intervention protocols. The methodology used to reach this objective was based on a detailed study about the application of robotic trainers developed in the last years for CP rehabilitation. This research identified the main limitations and challenges of current robotic therapies, which served as the base to design and develop a novel robotic platform in the framework of this thesis: CPWalker.

CPWalker is composed by two main parts: a smart walker and an exoskeleton with 6 degrees of freedom. Through them, it is possible to provide user's partial body weight support in parallel with guided joint motion and over-ground displacement.

CPWalker trainer promotes the progression of patients with CP into the rehabilitation treatment, increasing the level of intensity and frequency of the exercises as well as enhancing the motivation and tailoring the therapy to each user. To do so, innovative control strategies were used, which may be individually selected per joint giving a high versatility for the treatment's design.

The developed robotic platform was evaluated both technically and in clinical environments with pediatric patients. The results show the potential of the novel robotic platform to serve as a rehabilitation tool, also providing preliminary support for future clinical implementations not only in CPWalker, but also in other existing robotic gait trainers.

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Nomenclature

AAN	Assist-As-Needed
AFO	Ankle Foot Orthoses
BCI	Brain-Computer Interface
BMI	Brain-Machine Interface
CAN	Controller Area Network
CNS	Central Nervous System
CP	Cerebral Palsy
CSIC	Spanish National Research Council
CSTs	Corticospinal Tracts
CT	Crutches
DOFs	Degrees of Freedom
EEG	Electroencephalography
EMG	Electromyography
F	Force control mode
FAC	Functional Ambulation Category
FES	Functional Electrical Stimulation
FMS	Functional Mobility Scale
FO	Foot Orthoses
FSR	Force-Sensing Resistor
GGI	Gillette Gait Index
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure
gNEC	Neural and Cognitive Engineering group
HI	High Impedance control mode
HKAFO	Hip Knee Ankle Foot Orthoses
HNJ	Niño Jesús Hospital
HSP	Hereditary Spastic Paraparesis
IBV	Biomechanical Institute of Valencia
ICF-CY	International Classification of Functioning, Disability and Health framework, Children and Youth version

IMUs	Inertial Measurement Units
KAFO	Knee Ankle Foot Orthoses
LI	Low Impedance control mode
LRF	Laser Range Finder
MA	Melbourne Assessment
MACS	Manual Ability Classification System
MAS	Modified Ashworth Scale
MHRI	Multimodal Human-Robot Interface
MI	Medium Impedance control mode
NINDS	National Institute of Neurological Disorders and Stroke
NSCA	National Strength and Conditioning Association
P	Position control mode
PBWS	Partial Body Weight Support
PCI	Physiological Cost Index
PEDI	Pediatric Evaluation of Disability Inventory
PNS	Peripheral Nervous System
PW	Posterior Walker
PWM	Periventricular White Matter
QUEST	Quality of Upper Extremity Skills Test
RAGT	Robotic-Assisted Gait Training
RIC	Rehabilitation Institute of Chicago
ROM	Range Of Motion
SCALE	Selective Control Assessment of the Lower Extremity
SCI	Spinal Cord Injury
SCPE	Surveillance of Cerebral Palsy in Europe
SEMLS	Single Event Multilevel Surgery
TRL	Technology Readiness Level
UT	University of Twente
VR	Virtual Reality
WC	Wheelchair

F	Measured force
F_{error}	Error force
F_{ref}	Reference force
G_j	Subtask-specific gain
j	Specific subtask of walking
k	Stiffness of robotic assistance
$Perf$	Performance
R	Rotation matrix

R_G	Rotation matrix capture at the time of calibration
R_S	Rotation matrix captured in each instant
$T_{evaluation}$	Evaluation time of performance
tol	Tolerance
α	Euler angle in frontal plane
β	Euler angle in sagittal plane
γ	Euler angle in transversal plane
θ	Measured angle
θ_{error}	Error angle
θ_{ref}	Reference angle
$\chi_{default}$	Default control mode
χ_{new}	New control mode
Ψ	Challenge

Objectives, Motivation and Organization of Work

All of us were born with limitations, which we are continuously overcoming by the acquisition of capabilities during childhood, adolescence and adulthood. The faculty to obtain these capabilities depends on each person, being very often related to the person's attitude towards challenges of life. People with disabilities have major challenges to face during their development, however, the term "disability" is referred to the *difficulty to carry out particular or specific activities*, but it never means a total incapacity. People with disabilities are also full of skills and possibilities for the future, which in most of the cases will get better with effort.

Cerebral Palsy (CP) is the most frequent disability in childhood [1, 2]. It is caused by abnormal development or damage to parts of the brain, which very often are responsible of control movement, balance or posture, and to a lesser grade, they affect sensory or cognitive mechanisms. CP in childhood is associated with heavy demands on health, educational and social services, as well as on families and children themselves.

Early and ongoing rehabilitation treatments look for the improvement of capabilities of people with CP. The main therapies are [3]: i) *physical and occupational therapy*, which is focused on walking, standing, stretching exercises, and flexibility; ii) *oral medication*, which is generalized to spasticity treatment; iii) *orthoses*, which are normally used in children with CP to try to prevent deformities, contractures, and pain; iv) *botulinum toxin* to treat localized spasticity; v) *ferule and plaster* to avoid moderate contractures; vi) *multilevel orthopedic surgery*, which consists in two or more soft-tissue or bony surgical procedures, at two or more anatomical levels during one unique operative procedure [4]; vii) *partial body weight-supported treadmill training* and *constraint-induced movement therapy*, which are based on motor learning theories and promote the standardization of gait pattern by involving sensory information and reflection components of gait; and viii) *Robot-Assisted Gait Training* (RAGT), which may be an effective tool to compensate or rehabilitate the functional skills of people with CP [5].

In particular, rehabilitation robotics has been an emerging research field in the last years [6]. RAGT shows some promising advantages compared to conventional therapy [7], however, it should be further improved to increase its effectiveness, enhance motor learning and enrich recovery [7, 8]. The improvements of RAGT begin with the integration not only of Peripheral Nervous System (PNS) but also of Central Nervous System (CNS) into the human-robot loop. The parallel integration of both systems maximizes the therapeutic effects arising from the brain plasticity, which may be understood as the ability of the brain to change and thereby adapt the nervous system to physiologic changes and experiences [9]. Although this approach has been previously studied in other populations (e.g. Spinal Cord Injury (SCI) [10]), nowadays there is a lack of studies in CP [6]. On the other hand, recent studies suggest that RAGT should also include user's motivation and cognitive aspects as the attention as essential points to achieve a higher impact in physical abilities. In that sense, techniques that involve cooperative tasks (virtual reality (VR), training in real-life scenario or exercises with challenges for the patients) are being used, but still under development [7].

The main purpose of this work is to design, develop and evaluate a new robotic platform to improve the gait function of children with CP. Moreover, the author defines different strategies to implement into the robotic platform to be part of rehabilitation clinical protocols with children with CP. It is important to highlight that the target patients of this thesis (young children) have greater brain plasticity than adults [11], and are more likely to have a change in motor patterns following an intervention. According to this fact, it is essential to propose them physical exercises that increase their attention and motivation, delivering direct and causal feedback throughout the therapy. In order to fulfil the previous requirements and to provide a better solution for children with CP, various objectives are given below, which pursue two main goals: first, to design a new robotic platform that manages to improve the traditional gait rehabilitation; and second, to introduce new concepts and guidelines to allow novel therapies into the rehabilitation field. In a nutshell, the proposed objectives are:

- To develop a new robotic platform to support new therapies for gait rehabilitation of children with CP.
- To elaborate novel rehabilitation therapies based on the robotic platform in order to improve the traditional rehabilitation, tailoring the therapy to the patient's needs.
- To provide means for an objective evaluation of the robot-based rehabilitation therapies, based on the evaluation of the gait kinematic patterns, functional assessment and synergies generated.

- To validate the functional and usability benefits of the proposed robotic concept with final users (clinicians and patients).
- To evaluate the practical feasibility of the new system in clinical practice.
- To compare patients treated with traditional therapies with the ones treated with the therapies developed with this novel device.

Four hypotheses support these previous objectives:

- The rehabilitation with the proposed device will engage the users throughout therapy sessions. Patients will enhance their interest and motivation if the exercises are challenging, and thereby, the treatment outcomes will become better. With this goal, the device will use different technologies through which the CNS and PNS will be introduced in the rehabilitation.
- The ambulation treatment in real rehabilitation environments is a more challenging exercise than the rehabilitation on treadmill. If the patient's motivation is higher, the intensity and frequency of the therapy will increase. Moreover, children might create new brain connections and develop cognitive skills by exploring the world around them. This means that spatial cognition, problem solving and depth perception will be upgraded, which implies improvements in the outcomes of the treatment.
- The inclusion of novel algorithms to correct the child's posture and to enable the definition of tailored therapies for each patient will promote user's participation and may impact on brain reorganization.
- The early use of assistive technology in children with CP is considered a parameter of paramount importance to the results of the therapy. It is during these ages when brain plasticity is at its highest level, leading to the maximum capability for physical and cognitive rehabilitation.

Organization of work

The proposed methodology to achieve the objectives described in the previous section is based on an in-depth bibliographical study related to different fields of CP, in particular, technology used for gait rehabilitation. The work is divided into five chapters that partially overlap with the principal publications derived from the thesis [3, 12–14]. The chapters are organized as follow:

First chapter presents a general review of the state-of-the-art of CP rehabilitation. It starts describing the CP term and analysing the possible classification groups depending on different approaches. Subsequently, the chapter exposes an extensive review of the current treatments for patients with CP, with special emphasis on robotic rehabilitation [3]. The state-of-the-art of robotic devices for rehabilitation in CP is presented at the end of chapter 1. The rest of the dissertation is based on this preliminary research.

Although several existing robotic devices attempt to improve the gait training of children with CP and similar neurological and motor disorders, new challenges in robotic rehabilitation are needed in order to ratify its effectiveness and enrich current training protocols [7, 8, 15]. In this regard, chapter 2 establishes the main requirements for the development of a novel robotic platform for gait rehabilitation in CP. Both the mechanical design and control architecture of the platform are described in this chapter, going into detail about the different incorporated systems and their interaction [12]. The conclusions of chapter 2 will serve as the base to develop new algorithms and control strategies to implement innovative robot-based therapies.

The third chapter is focused on the definition and technical evaluation of elemental control strategies for robotic gait training in pediatric population. These strategies are based on a Multimodal Human-Robot Interface (MHRI) that makes the interaction between the patient and the robotic device. The control strategies are defined and evaluated using the gait trainer of this thesis, but they could also be applied to other rehabilitation platforms. Indeed, at the end of chapter 3, the author exposes how a controller developed within the framework of this dissertation, has been transferred to other domains. A preliminary validation of the control strategies on real patients provided important outcomes to define a robot-based gait training proposal [13].

Chapter 4 covers the goal settings and detailed guidelines of an accurate robot-based program for gait rehabilitation of pediatric population with CP [14]. This rehabilitation program tries to improve patients' capabilities related to diverse functional domains of the International Classification of Functioning, Disability and Health framework, Children and Youth version (ICF-CY) [16]. Two gait training phases (*strength phase and power phase*) are considered, which are validated in four children with CP as preliminary support for future clinical implementations. At the end of the chapter, the author presents a discussion of the obtained results.

Chapter 5 summarizes the main conclusions and identifies major contributions of this work. Furthermore, it presents the future work derived from the outcomes of this dissertation.

Bibliography is exposed at the end of the thesis.

Chapter 1

Introduction to Cerebral Palsy and Gait Rehabilitation

In the last decades, studies about rehabilitation in Cerebral Palsy have increased, placing emphasis on promoting active therapies with high intensity and repetitive and task-specific training in order to enhance neuroplasticity. Robot-based treatment for gait rehabilitation is a novel approach, currently under development, which drives the patient's gait in special conditions enhancing the progress of the therapy.

This chapter presents an overview of the Cerebral Palsy pathology, its main risk factors and classification scales. The chapter highlights the principal therapies carried out in rehabilitation of Cerebral Palsy, and focuses on emerged robotic technologies reviewing the current devices used with this aim. Finally, the chapter also identifies the main shortcomings on current robotic trainers in order to define a new device for gait rehabilitation in Cerebral Palsy and related disorders.

1.1 Cerebral Palsy

CP term could be defined, according to the National Institute of Neurological Disorders and Stroke (NINDS), as "any one of a number of neurological disorders that appear in infancy or early childhood and permanently affect body movement and muscle coordination but do not worsen over time". These disorders can disturb other higher functions and infer in the CNS. Nevertheless, the definition of CP remains a controversial issue at the present time. The universal acceptance of one definition of CP does not exist, but it is often associated with sensory deficits, cognition impairments, communication and motor disabilities, behaviour issues, seizure disorder, pain, and secondary musculoskeletal problems [17]. Movement and posture disorders derived from CP are generally characterized by loss of muscle strength, improper muscle activation and loss of coordination [18].

This disease is more common in males, and the main causes and risk factors are: multiple birth, extreme prematurity, birth asphyxia, feeding issues, prolonged hospitalization, or postnatal infection [19]. So far, CP has been diagnosed between 12 and 24 months of age, but nowadays, it is possible an early diagnosis at 12 weeks of age for roughly half the affected population, via the evaluation of risk factors previously given [19].

The overall rate of CP for the period of 1980 to 1990 was 2.08/1000 live births (95% CI 2.02 to 2.14) [20, 21]. One in five children with CP (20.2%) had a severe intellectual deficit and was unable to walk. Among babies that weighed less than 1500 g at birth, the rate of CP was more than 70 times higher than those weighing 2500 g or more at birth. The rate of CP rose during the 1970s but remained constant during the late 1980s [21]. It was also maintained about constant from 1980s to through 2002, rather than increasing as might be expected [2]. The rate of multiple births in the population increased from 1.9% in 1980 to 2.4% in 1990, and the proportion of multiples among infants with CP increased from 4.6% in 1976 to 10% in 1990. Multiples have a four-fold higher rate of CP than singletons overall [20, 22]. Recent studies affirm that the current prevalence of CP is 2.11/1000 births (95% CI 1.98-2,25) [1, 2].

In the last years, the improvements in care during pregnancy and after birth have prevented cases of CP with severe intellectual disability (prevalence for these cases decreased about 2.6% each year from 1985 to 2002, [2]).

1.2 Classification of Cerebral Palsy

The CP term covers a quite heterogeneous groups of disorders, and therefore, it is difficult to classify the type of CP suffered by a patient. In accordance with the Spanish confederation for the care of people with CP [23], individuals with CP are normally categorized into classes or groups, though most people with CP have a combination or two or more types. From a topographic point of view, depending on how many structures are involved (see Figure 1.1), people with CP could be classified as having Hemiplegia, Paraplegia, Tetraplegia, Diplegia, or Monoplegia [23]:

- **Hemiplegia**: Only one side of the body affected, including arm, leg and trunk.
- **Paraplegia**: Lower limbs affected.
- **Tetraplegia**: Lower limbs and upper limbs affected.

- **Diplegia**: The most affected limbs are the lower limbs.
- **Monoplegia**: Only one limb is affected, usually an arm.

This classification, used in combination with the type of movement disorder (Spasticity, Dyskinesia/Athetoid, Ataxia, or Mixed), offers an interesting approach for clinical practice. Table 1.1 shows the description of each movement disorder in CP according to "Surveillance of Cerebral Palsy in Europe" (SCPE) [24].

On the other hand, functional classification procedures are recommended when a clinical decision is required. In order to categorize the degree of involvement, the most used scale is the "Gross Motor Function Classification System" (GMFCS) from Palisano et al. in 1997 [25], which was revised in 2007. It defines five levels of CP depending on functional limitations (Figure 1.2), the need for hand-held mobility devices (such as walkers, crutches or canes) or wheeled mobility, and to a much lesser extent, quality of movement. This bibliography also recognizes that the levels of GMFCS are based on age (groups under two years old, between two and four years old, between four and six years old, between six and 12 years old and between 12 and 18 years old):

- **Level I**: Walks without limitations.
- **Level II**: Walks with limitations in long distances and balancing. They may need a hand-held mobility device to learn to walk for the first time. They require some support to walk up and down stairs.
- **Level III**: Walks using a hand-held mobility device.
- **Level IV**: Self-mobility with limitations. They may use powered mobility.
- **Level V**: Has severe limitations in head and trunk control. They are transported in a manual wheelchair, and self-mobility is only achieved if the child is able to learn how to operate a powered wheelchair.

FIGURE 1.1: Types of CP depending on structures involved.

Table 1.1: Types of movement disorders in CP according to Surveillance of Cerebral Palsy in Europe (SCPE)

Spastic CP	- Abnormal pattern of posture and/or movement. - Increased tone. - Pathological reflexes. - Spastic CP may be either bilateral or unilateral: · It is bilateral if limbs on both sides of the body are involved. · It is unilateral if limbs on one side of the body are involved.
Dyskinetic or Athetoid CP	- Involuntary, uncontrolled, recurring, occasionally stereotyped movements. - Abnormal pattern of posture and/or movement. - Spastic CP may be either dystonic or choreo-athetotic: · Dystonic CP is dominated by both hypokinesia and hypertonia. · Choreo-athetotic CP is dominated by both hyperkinesia and hypotonia.
Ataxic CP	- Abnormal pattern of posture and/or movement. - Loss of orderly muscular coordination used to perform movements with abnormal force, rhythm and accuracy.
Mixed CP	- Combined several types of CP.

Another evaluative method is the "Functional Mobility Scale" (FMS) [26], which is utilized to measure functional mobility over three distinct distances (5 m, 50 m and 500 m), specifying the assistive device that the child needs to use. In line with the GMFCS and the FMS, severity is also used for classification purposes (Moderate, Moderately severe, or Severe CP).

Finally, taking into account the measure on fine motor function, the "Manual Ability Classification System" (MACS) [27] classifies the use of hands in users with CP to perform activities of daily life. Other scales as "Modified Ashworth Scale" (MAS) or "Tardieu Scale" have the purpose of measuring spasticity in patients with CP. They are a quick and easy form that can assist a clinician's assessment of spasticity during passive soft-tissue stretching.

However, in spite of all these metrics, in most cases it is difficult to classify a patient due to the wide variety of alterations and levels of severity.

FIGURE 1.2: Levels of Gross Motor Function Classification System (GMFCS).

1.3 Current therapies for patients with CP

A complete cure for CP is not currently available, because this means repair of the underlying brain damage. Therefore, rehabilitation is commonly used with the principal aim of improving patient's independence in daily life [6] and preventing secondary complications. If secondary musculoskeletal disorders appear and they are persistent, some factors emerge such as gait impairments, abnormal muscle tone, fatigue, weakness, communication impairments and loss of function.

Therapies for CP and their mode of application depend on the specific patient's disorders and severity, and they range from physical therapy to medication and surgery. However, under all conditions, rehabilitation needs to be implemented during the early stages of child's development, because it is at this phase when fundamental abilities and skills are developed [28]. These abilities include activities of daily living as playing, self-care activities and fine motor tasks (writing, reading or drawing). The success rate of rehabilitation also increases in accordance with the intensity of therapy, repetition, and patient's motivation, the latest specially in children [6]. As a result, it is essential to give children with CP the opportunity to interact with the environment looking for an integral development (physical and cognitive).

The estimated cost to care for an individual with CP is a real problem for families and caregivers, and it is around $1 million. The combined estimated lifetime costs for all people with CP who were born in 2000 will total $11.5 billion in direct and indirect costs [22].

Next subsections summarize the main therapies carried out so far for rehabilitation of people with CP [3].

1.3.1 Physical and occupational therapy

Physical therapy is a part of rehabilitation that tries to restore, maintain and promote patient's optimal movement and physical function. The main goal of the physical therapy is to maximize functional control of the body, or increase gross motor function. There are a wide variety of exercises that are carried out in physical therapy for CP [29], but in general, they are focused on walking, standing, stretching exercises, and flexibility. Physical therapy should be always guided by a physiotherapist, who can benefit from different instruments as bars, treadmill and other adaptive equipment designed to achieve mobility, but also could involve robotic devices to implement the exercises. In the last case, it is called "robotic physical therapy".

1.3.2 Oral medication and botulinum toxin

Some drugs could be indicated in CP cases in which the distribution of muscle overactivity is diffuse. In particular, the main current approved agents to treat spasticity in CP are baclofen and diazepam. From the end of 20^{th} century, botulinum toxin type-A has been used to complement the existing oral medication for treating spasticity, mainly focused on motor problems of children with CP [30]. The principal difference between both oral medication and botulinum toxin is that the effects of the latest could be localized for a specific region of the body.

1.3.3 Orthoses and technical supports

Technical support is defined as any product developed with the aim of preventing, compensating or neutralizing activities limitations or restrictions in the participation. Devices for gait technical support in CP are primarily designed to allow autonomous displacement to the patient, improving functional independence and social integration. In a second way, they try to prevent deformities, contractures, and pain. As a consequence, user's quality of life is changed for the better.

The whole of technical aids in children with CP is extremely diverse, and it may range from orthoses (Figure 1.3) to canes, crutches and walkers (Figure 1.4):

- **Orthoses**: They are external supports that can be adapted individually for each patient. Their aim is to modify the structural or functional conditions of the neuromusculoskeletal human system. In CP, orthoses are normally used to reinforce and protect a surgical procedure during a rehabilitation period. With them, the

FIGURE 1.3: Types of orthoses for children with movement disorders. (a) Foot orthoses (FO); (b) Ankle Foot orthoses (AFO); (c) Knee Ankle Foot orthoses (KAFO); (d) Hip Knee Ankle Foot orthoses (HKAFO).

development of growth abnormalities are limited and the gait is improved [31]. There are some types of orthoses depending on the body segment that is utilised:

- Foot orthoses (FO): Normally used as insoles, Figure 1.3 (a).
- Ankle Foot orthoses (AFO): The most applied in CP to prevent equinus foot, Figure 1.3 (b).
- Knee Ankle Foot orthoses (KAFO): They are not very common in CP treatments, Figure 1.3 (c).
- Hip Knee Ankle Foot orthoses (HKAFO): They are rarely used today in children with CP. They control lateral movements and spasticity, Figure 1.3 (d).

• **Walkers**: They are useful devices to assist people in walking actions. For its use, it is necessary the presence of motor control as the patient's capacity of head control and weight discharge in lower limbs [32]. There are some types of walkers, but the most used are anterior walkers (positioned in front and moved forward by the user, Figure 1.4 (a)) and posterior walkers (the person pulls from behind, Figure 1.4 (b)). Some studies in the bibliography affirm that posterior walkers have more advantages in terms of upright positioning and energy conservation than anterior walkers [33]. Moreover, posterior walkers could be more favourables since the person's center of mass is within the base of support of the walker.

1.3.4 Orthopaedic surgery

Most of current basic treatments applied with the aim of improving the mobility in patients with CP, are not effective at some specific age (observe Figure 1.5) [34]. With the child's growth, deformities in bones increase, and muscles on hip, knee and ankle work in a worse way contributing to the development of crouch gait (Figure 1.6). The progress

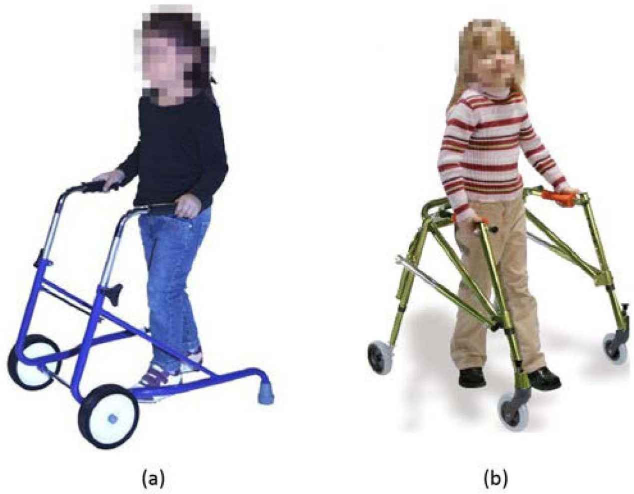


FIGURE 1.4: Types of walkers for children with movement disorders. (a) Anterior walker; (b) Posterior walker.

of crouch gait linked to a pubertal growth spurt, generates knee pain, a decrement of endurance, and the necessity of using gait assistive devices [4].

To address the limitation of progressive musculoskeletal disorders, orthopaedic procedures have been designed. One of the most important concepts in this field is the "Single Event Multilevel Surgery" (SEMLS), adopted by Nene et al. in 1993 [35]. It may be understood as a type of surgery in which multiple levels of musculoskeletal pathology in both lower limbs are addressed by two surgical teams during only one operative procedure. It requires only one hospitalization and one rehabilitation period [4, 34, 36]. The

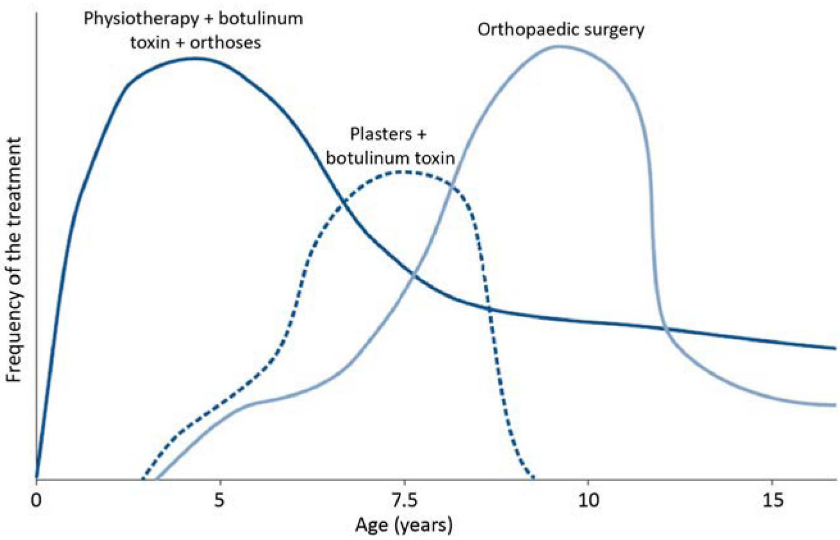


FIGURE 1.5: Treatment applied during the growth of children with CP. Frequency peak for SEMLS is achieved in puberty stage.

FIGURE 1.6: Stiff knee flexo in a patient with CP.

most common gait pattern treated with SEMLS corresponds with crouch gait combined with knee flexion, hip flexion and ankle dorsi-flexion [32].

SEMLS technique has demonstrated important benefits in musculoskeletal problems of children with CP, reducing walking effort [35], improving the "Gross Motor Function Measure" (GMFM) [37, 38] and kinematic parameters [39], gait speed [40] and the Gillette Gait Index (GGI) [41]. However, it should be only applied if conservative treatments were not enough to stop the progressive deterioration of patient's ambulation.

Current conventional rehabilitation techniques after a surgical procedure in CP are mainly carried out in four stages, which following chronological order in rehabilitation period, they are: i) in first phases after surgical process we found early mobilization, cryotherapy, active and resisted kinesiotherapy of non-operated limb and isometric contraction of operated limb; ii) analytical and resisted kinesiotherapy of operated limb, stretching exercises and trunk and postural control exercises; iii) in more advanced rehabilitation stages we found dissociation of limbs, weight transfer exercises and changing between sitting and standing position; and iv) muscle strengthening machine, balance exercises, squats, stairs and parallel bars.

1.3.5 Robotic physical therapy

Recently, several technological advancements have been introduced into the field of rehabilitation to complement conventional therapeutic interventions. In the light of this, robot-assisted therapy appears as an alternative and complementary treatment [6]. It could be defined as a form of physical therapy that uses a non-invasive robotic device to help a person with an impaired functional ability to recover their function [42]. Robot-assisted training increases the therapy compliance by proposing goal-directed tasks that encourage the patients. This approach has interesting advantages compared to traditional therapy, because it suggests functional exercises with accurate and assembled movements, instead of repetitive movements without goals. Moreover, robotic trainers reduce the physical load and cost of conventional therapies, integrating at the same time novel systems to objectively measure the progression of the exercise. As a result, the number of sessions, frequency, intensity, and finally the positive impact of the treatment are typically increased.

Robotic devices may sometimes be combined with new and advanced methods of feedback, as the application of virtual scenarios, where the users can interact with a virtual object in real-time and feel that they are part of a virtual environment during the therapy [6, 43]. In that sense, there is widespread interest in using VR in the rehabilitation of children with CP to address upper [44, 45] and lower extremity motor functions [46, 47].

On the other hand, robot-assisted gait therapy is also often combined with partial body weight support (PBWS) [48–50], providing beneficial results specially in patients with low ambulatory status. This feature allows repetitive execution of gait movements in a controlled and safe way, with an adjustable support of body weight, which is sometimes in high demand by the therapists. Generally, training protocols include a gradual increase of difficulty level by decreasing the amount of PBWS provided during walking.

Nevertheless, although some features of using robot-based therapies have demonstrated positive results compared to traditional training in different pathologies, there is a weak evidence regarding the use of RAGT in case of children with gait disorders [8, 51]. With the main aim of addressing this fact, this thesis proposes a novel solution based on robotic rehabilitation as part of the gait training for patients with CP. In order to better understand the robotic field, and to know the existing alternatives, next section gives an (incomplete) overview of robotic devices that are currently used for rehabilitation of children with CP, both upper and lower limbs. This will serve to discuss the challenges that are needed to fulfil, and it will provide the background for a new proposal of robotic gait trainer.

1.4 State-of-the-art of robotic devices for rehabilitation in CP

Robotic rehabilitation has been a growing research field in the last years. Most of the robotic devices were initially designed for spinal cord injury or stroke patients, and they are being recently adapted for people with CP. Within CP, pediatric population with CP is one of the last groups in which these technologies are being applied. In this case, there is still no standardization about clinical conditions, time or outcome measures used. For this reason, it is difficult to describe and precisely quantify the benefits of robot-based therapy in children suffering of CP. Additionally, a more detailed description of user's profile is required, specially in case of users with CP, whose motor particularities are very heterogeneous.

This section gives a general overview of the current robotic devices to implement rehabilitation in CP. According to that, both cases upper and lower limbs are necessary to be reviewed to understand the last advances in robot-assisted rehabilitation for CP. The review provides a framework to finally identify the lacks in devices for lower limbs in order to look for a better robotic solution for gait rehabilitation of children with CP.

1.4.1 Robot-assisted rehabilitation for upper limbs

There are currently a limited number of robotic systems targeting the upper extremity that have been applied to children with CP [52]. These devices work via goal-directed tasks and reaching movements to rehabilitate hand and arm function.

The InMotion2 (Figure 1.7 (a)), also called the shoulder-elbow robot, is an end-effector robot, a commercial version of MIT-MANUS (Interactive Motion Technologies, United States) [53], which is capable of continuously adapting to and challenging each patient's ability. This device aims to improve the patient's range of motion, coordination, strength, movement speed, and smoothness. 117 subjects that had previous strokes were trained with InMotion2, and during the training patients were able to execute shoulder and elbow joint movements with significantly greater independence. At the end of the experiment, the subjects were better able to draw circles [54]. In most cases, studies conducted with stroke patients have encouraged new experiments with people with CP, as in another experiment where 12 children aged 5-12 years with CP and upper-limb hemiplegia received robotic therapy twice a week for 8 weeks. The children showed significant improvement in their total Quality of Upper Extremity Skills Test (QUEST) and Fugl-Meyer Assessment scores [53]. Following the distal approach, Interactive Motion Technologies developed the MIT-Manus InMotion3, which works with flexion, extension, pronation, and supination of the affected wrist. The results are similar to those of InMotion2, but in this case, InMotion3 can operate both as a standalone device and as an InMotion2 module; InMotion3 has not yet been used in studies that include children with CP.

Another robotic system for the upper limbs is the New Jersey Institute of Technology's Robot-Assisted Virtual Rehabilitation System. It is comprised of a HapicMaster and a custom-made ring gimbal (represented in Figure 1.7 (b)). This system has 6 Degrees

FIGURE 1.7: Robots for upper limbs rehabilitation. (a) InMotion (Interactive Motion Technologies); (b) HapicMaster; (c) Armeo (Hocoma AG); (d) YouGrabber (YouRehab); (e) REAPlan.

of Freedom (DOF) and is a force-controlled haptic interface [6]; it provides the user with a realistic haptic sensation and the power to closely simulate the weight and force found in a wide variety of human tasks. The programmable robot arm utilizes the admittance control paradigm, giving the device unique haptic specifications, and was used in combination with virtual scenarios to improve shoulder and elbow movements [55]. In a study that tested 9 patients with CP, who performed 9 sessions (60 minutes each) of 3-timed upper extremity tasks and several measurements of reaching kinematics, the patients improved in measures of motor activity in the Melbourne Assessment (MA) after treatment [6].

The ARMEO (Hocoma AG) system (based on the T-WREX system) proposes a rehabilitative exercise that allows early rehabilitation of motor abilities and provides adaptive arm support in a 3D workspace (Figure 1.7 (c)). The ARMEO system is focused on patients that lack sufficient strength to move their arm and hand against gravity [56]. Some springs can support the weight of the upper and lower arm [6], and the system may be adapted for each child. Unfortunately, no clinical trials have been found with this system and people with CP.

The YouGrabber System (Figure 1.7 (d)), developed by YouRehab Company, Switzerland, is a virtual rehabilitation system based on video games that uses a pair of data gloves and an infrared camera to capture the fingers flexion. This system allows mirror movement training, and a particular advantage of YouGrabber is its ability to provide both unilateral and bilateral training [57]. The games are based on reach, grip, and transport tasks [6]. In the first study, 5 children with motor deficits in upper limbs were tested with YouGrabber. The experiment was developed in 9 sessions of 45 minutes each, and the tasks involved hand grasping and releasing, wrist pronation and supination, and arm reaching. Results were satisfactory: 4 out of 5 patients showed improvements in all measures in the MA [58].

Gilliaux et al. [59, 60] assessed another robot-assisted therapy (REAPlan, see Figure 1.7 (e)) through a single-blind randomized trial. The REAPlan is a distal effector robot that allows for displacements of upper limb in horizontal plane. 16 children with CP were randomized into two groups: a control group of 8 users conducting 5 conventional therapy sessions per week over 8 weeks and a robotic group of 8 users conducting 3 conventional therapy sessions and 2 robot-assisted sessions per week over 8 weeks. Outcome measures, such as QUEST and PEDI (Pediatric Evaluation of Disability Inventory) were analysed. According to the author, there was evidence that the robotic therapy was effective since the outcome measures improved significantly more in the robotic group than in the control group; the authors also suggested studying the long-term effects of the therapy.

A classification of the most used devices for CP focused on upper limbs is shown in Table 1.2.

1.4.2 Robot-assisted rehabilitation for lower limbs

One of the main goals of neuromotor rehabilitation is the recovery of locomotion ability, because it allows patients to improve their independence and quality of life. In this framework, robotics is emerging as a leading technology for motor rehabilitation of subjects with neurological impairments and, in particular, the recovery of walking. As was previously exposed, RAGT has some promising advantages over traditional training, because it is intensive, controlled, repetitive, and provided with goal-oriented tasks, which is known to be related to cortical organization and motor learning processes [61]. This aspect is particularly important for pediatric population, who could obtain better results thanks to their higher neuroplasticity.

In general, there are basically two groups of assistive robotic devices to help people with mobility problems: alternative devices and empowering (or augmentative) ones. These solutions are selected based on the degree of the user's disability. In case of total incapacity of mobility (including both bipedestation and locomotion), alternative solutions are used, such as wheelchairs or special vehicles. On the other hand, people who have reduced mobility, commonly use augmentative devices that utilize their residual capabilities, e.g. walkers and exoskeleton robots are augmentative devices that assist in standing, balance, and locomotion [62]:

TABLE 1.2: Overview of devices for CP focused on upper limbs

Device	Number of patients	Therapies and measurements	Results
InMotion2 [53]	12	Robotic therapy twice a week for 8 weeks	Improvements in total QUEST and Fugl-Meyer Assessment Scores
HapicMaster [6]	9	Composite of 3 timed upper extremity task and several measurements of reaching kinematics	Improvements in measures of motor activity in the MA
YouGrabber [58]	5	- 9 sessions of 45 min each one - The task carried out involved hand grasping and releasing, wrist pronation an supination and arm reaching	4 of 5 patients showed improvements in all assessments (MA)
REAPlan [59]	16	In robotic group, 8 users conducting 3 conventional therapy sessions and 2 robot-assisted sessions per week over 8 weeks	Measures such as QUEST and PEDI were analyzed. There is evidence that robotic therapy is effective since outcome measures improved significantly more in the robotic group than in the control group. Long term effects of the therapy

- **Robotic walkers:** Walkers are intended to help users' navigation providing balance support. They take advantage of the user's remaining locomotion capability, and also help to avoid the early and deteriorative use of alternative devices, most commonly wheelchairs. "Smart walkers" are robotic devices based on walkers that are optimized to improve the human-machine interaction and, as a result, to improve the acceptance and functionality of these systems in rehabilitation.

- **Exoskeletons:** Exoskeletons are mechatronic devices whose segments and joints correspond to some extent to those of the human body and the system is externally coupled to the person. In rehabilitation applications, exoskeletons should be able to replicate, with a patient, the movements performed with a therapist during the treatment. In the case of functional compensation, exoskeletons are designed to support the execution of activities of daily living by assisting the user in the basic motor functions. The exoskeletons were intended to provide either joint support by means of brakes or clutches [63–66] or actively add power to the joints, thus providing a means to control and complete joint movements [67–70]. In addition, sensors attached to exoskeletons can assess patient's forces and movements, which would give the therapist quantitative feedback regarding the patient's recovery and rehabilitation process. Therefore, exoskeletons could act as a tool for the measurement of the performance and evolution of the treatment [71].

The number of robotic devices (comprehending walkers and exoskeletons) that have been developed or adapted for gait rehabilitation of CP is growing from the last years. The most important ones could be summarized as: i) NF-Walker [72]; ii) Innowalk-Pro [73]; iii) Lokomat [74]; iv) GT1RehaStim [75]; v) Walkbot [76]; vi) Autoambulator; and vii) Multi-robot [77], (all of them represented in Figure 1.8). Their analysis (given below) present some outcomes obtained in relevant studies carried out with each device. The advantages and disadvantages of the current robotic gait trainers when are used in pediatric population with CP, will be also examined.

The NF-Walker is a commercially available device that illustrates the use of robotics for the assistance of people with CP (Figure 1.8 (a)). It is a hybrid assistive device that gives dynamic support to standing position and gait. The user's weight is discharged by the wheels of the device [72]. This platform provides motor stimulation for users and gives them a sense of accomplishment. It can be individually adapted to the user, who is supported in an upright and corrected position with both hands free. The NF-Walker was developed by Made for Movement, Norway. To evaluate the applicability of this robotic walking aid in non-ambulatory children with CP, Smania et al. [78] conducted an experiment with an 11-year-old boy (GMFCS IV) that was unable to walk independently due to spastic tetraparesis. The outcomes measures were: 2-minute

FIGURE 1.8: Robotic-assisted gait trainers in CP. (a) NF-Walker; (b) Innowalk-Pro; (c)Lokomat; (d) GT1RehaStim; (e) Walkbot; (f) Autoambulator; (g) Multi-robot.

walking test, 10-meter walking test, respiratory and heart parameters, and energy cost of locomotion. The results were satisfactory in most of the tests, suggesting that the NF-Walker may allow children suffering from CP with severe gait impairment to move around in their environment. This device may potentially stimulate the development of gait in children with neurological gait impairment.

Other devices developed by Made for Movement are Innowalk and Innowalk-Pro (Figure 1.8 (b)). Both Innowalk and Innowalk-Pro are robots intended for rehabilitation programs with PBWS that can induce healthy gait patterns in their users. Innowalk gives disabled people (including CP) the opportunity to experience assisted, guided, and repetitive movement, which is very beneficial for rehabilitation after surgery, and provides steady and corrected leg movement in sitting and/or standing positions [73]. With the Innowalk-Pro, the upper limbs, lower limbs and Innowalk movements are coordinated as part of the therapy [79]. The Innowalk and Innowalk-Pro are static devices because the patient does not move through the room. In [80], 5 children with GMFCS scores between III and V were chosen for an experiment where they had to use the Innowalk for 4 weeks (5 times per week, 30 minutes per day). At the end of the study, 4 of 5 children had increased muscle mass, 3 of 5 improved their joint deflection, and all of them improved their posture control. Moreover, 72.2% of patients' caregivers stated that the child enjoyed using Innowalk, while 85.1% stated that Innowalk helped to maintain the child's function [73].

Lokomat (Figure 1.8 (c)) is a robotic platform designed by Hocoma AG, Switzerland [74] for the treatment of RAGT in adults and children affected by different pathologies as stroke or CP. This device is the most widely used hospital rehabilitation robotic platform worldwide. Pediatric Lokomat is adapted to the individual patient's anatomy. Its concept is similar to the Innowalk in that it practices rehabilitation therapies using repetitive movements. The Lokomat consists of a 2-leg exoskeleton with motor drives, a PBWS, and a synchronized treadmill. Several studies have been conducted with Lokomat, e.g. a study developed with 16 users that had previous strokes demonstrated that after treatment all patients had improved gait performance and motor function; although 5 patients were initially unable to walk in the Lokomat for 30 minutes, they succeeded in doing so within 1 to 3 days [81]. In another study that included patients with CP, 33 patients (nine females and 24 males, all around 7 years of age; all GMFCS III initially) underwent 40 Lokomat sessions; after the 40 sessions of 20 minutes each, 8 users (24%) could walk without assistance and achieved GMFCS II, and 15.3% of the remaining patients showed improvements in their gait pattern [82]. Borggraefe et al. [83] showed positive effects after 12 training sessions with the Lokomat and described improvements in standing and walking ability (dimensions D and E of the GMFM, respectively) in 20 children with bilateral CP, which were maintained after a period of 6 months. The authors also reported the intervention's efficacy was dose-dependent, as the improvements in the task (walking) measured in dimension E of the GMFM were positively correlated with higher distance and time walked.

Another system for robotic-assisted gait training available in the market for the rehabilitation of children with CP is the Gait Trainer GT-1 RehaStim (Figure 1.8 (d)), which aims to improve the patient's ability to walk through repetitive training. The weight of the user is relieved and children are positioned on two footplates that simulate the stance and swing phases of gait [75]. A recent study checked the effectiveness of this device compared to conventional training in 18 children with diplegia or tetraplegia. The GT-1 group received 30 minutes of robot training plus 10 minutes of stretching exercises, while the control group received 40 minutes of conventional physiotherapy; all the subjects underwent 10 sessions over a 2-week period. The results were satisfactory for the experimental group, showing improvements on the 10-meter walk test, 6-minute walk test, hip kinematics, speed, and step length, which was maintained 1 month after the treatment had finished [75].

Finally, other novel rehabilitation devices for CP are Autoambulator (HealthSouth, United States), Walkbot (Walkbot, South Korea) and Multi-robot (Harvard University, [77]), Figure 1.8 (e), (f), (g), respectively.

Table 1.3 summarizes the described studies for the most relevant robotic devices for gait rehabilitation in CP.

Based on this, author concludes that robotic gait trainers is one of the best solutions for rehabilitation in CP. However, most of therapies performed with the current robotic gait trainers are peripherally driven and are based on motor control reorganization triggered by peripheral physical therapy. There is evidence that CP affects primarily brain structures, so this suggests that for a proper rehabilitation, both PNS and CNS should be integrated in a physical and cognitive therapy. Moreover, although all of the current technological devices allow more intense sessions, the exercises proposed are not complete at all. The robotic training should be further optimized to fit better into motor learning and recovery, as well as neural plasticity. To do so, the training has to be made more task specific, encouraging the patients to an active participation and facilitating functional improvement [84].

Table 1.4 gives a general vision the main characteristics, advantages and weaknesses of the presented robotic devices, with the main aim of clarifying the challenges in this field. These challenges will be used as a background to develop the new proposal for robotic gait training, which is the principal objective of this doctoral thesis.

1.5 Conclusions

This chapter presented a general introduction about CP disability, its classification and therapies carried out for the rehabilitation of patients, particularly when they are children. The definition adopted for CP encompasses several disorders of posture and movement due to a defect or lesion in the immature brain [17]. Although there are some classification procedures to categorize CP into different levels, it is a challenge not met in full.

CP affects many different body functionalities (e.g. cognitive disabilities, epilepsy, vision or speech impairments...), but particularly, the number of patients with CP suffering from pathological gait patterns is very high. Gait disorders in CP are enhanced when the children grow up and they increase their weight. To treat it, there are some types of therapies that look for a better quality of life. From a physical rehabilitation point of view, the therapies have been classified as conventional physical rehabilitation or robot-based therapies, depending on the resources employed in each case.

TABLE 1.3: The most relevant robotic platforms for lower limbs in CP

Device	Number of patients	Therapies and measurements	Results
NF-Walker [72]	1	- 2 min walking test - 10m walking test - Respiratory and heart parameters - Energy cost of locomotion	Improvements in all test. Use of NF-Walker may help children with severe impairment of gait as a result of CP
Innowalk [80]	5	Session training: 30 min/day; 5 days/week; 4 weeks	4 of 5 children increased muscle masss, 3 of 5 improved their joint deflection, and all of them improved their posture control
Lokomat [82, 83]	33	40 sessions of 20 minutes each	8 users could walk without assistance and the 15.3% of the rest of the patients had an improvement in their gait pattern
GT1 RehaStim [75]	18	- 30 min of robot training + 10 min of stretching exercises - 10m walk test - 6 min walk test - Hip kinematics, speed and step length	The results were satisfactory in all the experiments and maintained 1 month after the treatment had finished

Table 1.4: Main characteristics and shortcomings in current robotic devices for gait rehabilitation of children with CP. The gait exercises can be implemented through over-ground walking (OW), treadmill training (TT) or foot plates (FP), depending on the device

Device	Type	Characteristics	Challenges
NF-Walker	Assistance	OW	- Guided movement - PBWS - Active postural control - Task specific training
Innowalk-Pro	Rehabilitation	FP	- CNS inclusion - PBWS - Active postural control - Task specific training - Over-ground experience
Lokomat	Rehabilitation	TT	- CNS inclusion - Active postural control - Task specific training - Over-ground experience - Arm movement
GT-1 RehaStim	Rehabilitation	FP	- CNS inclusion - Active postural control - Task specific training - Over-ground experience - Arm movement
Autoambulator	Rehabilitation	TT	- CNS inclusion - Active postural control - Task specific training - Over-ground experience - Arm movement
Walkbot	Rehabilitation	TT	- CNS inclusion - Active postural control - Task specific training - Over-ground experience - Arm movement
Multi-robot	Rehabilitation	TT	- Guided movement - Active postural control - Task specific training - Over-ground experience

The main disadvantages founded for conventional therapies were the limitation due to therapist's physical effort and the lack of durability of the sessions (specially in lower limbs rehabilitation). Moreover, guided movements of the user's joints do not perform an exact pattern because the human intervention into the treatment is very high. For this reason, robotic therapy appeared. Robotic devices for rehabilitation in patients with CP reduce the therapists' workload compared to traditional training, and they continuously guide the patient's lower or upper limbs following physiological patterns, with high repetition accuracy and prolonged training duration.

Clinical experience of gait rehabilitation suggests that gait training in children could be conducted even more effectively using robot-based therapy rather than conventional strategies [42]. The most important robotic devices for gait assistance and rehabilitation in CP were presented, highlighting their principal studies, advantages and weaknesses. As a brief recapitulation, most of the current devices use PBWS at a time that provide guided and repetitive movement of the lower limbs. Nevertheless, the majority of these available gait trainers do not integrate the CNS into the therapy and the exercises are not tailored for the specific patient's needs. Evaluations with the most common available devices for rehabilitation have been mostly carried out following position control mode instead of training with "assist as needed" strategy [85]. Moreover, they avoid to correct the posture during walking and do not allow free movement in real environment. A new device with the goal of including all the advantages of current treatments in only one equipment is necessary. This novel system should incorporate new strategies that address the presented limitations, providing facilities to tailor the therapies to the patients. In that form, a better and complete rehabilitation will be achieved.

On the other hand, there is a lack of published recommendations regarding the most efficient rehabilitation program [37], which should specify the treatment duration and provide guidelines to introduce the robot-based rehabilitation into the clinical practice. It is necessary a new proposal for gait rehabilitation in users with CP and similar motor disorders. New strategies are needed to help to promote, maintain, and rehabilitate the functional capacity, and thereby diminish the dedication and assistance required and the economical demands that CP represents for the patients, the families and the caregivers.

Chapter 2

Design of a Robot-Assisted Gait Trainer for Children with Cerebral Palsy: CPWalker

Although several impairments interfere with the quality of life of children with CP (seizure disorders, hearing and visual problems, cognitive and attentional deficits...), mobility impairment is the hallmark of this disease [17]. Mobility impairments have special influence on the child's development, characterizing gait by reduced speed and endurance or shortened step length [86]. In last decades, robotic strategies for gait rehabilitation in CP have complemented conventional therapies, demonstrating improvements in kinematics, gait speed and endurance of these patients [61, 75, 87–90]. Several robotic devices appeared in the market to treat CP, nevertheless so far there is no study that provides a depth and complete assessment of robot-based therapies in the treatment of children with CP. Further research is crucial both in device design and clinical interventions in order to validate effectiveness and clarify training protocols [7, 8, 15, 51].

This chapter presents a new robotic platform to support novel therapies for gait rehabilitation in CP: "CPWalker". CPWalker represents a new approach for gait training in children, which overcomes the challenges exposed for the current robotic devices. The specific patients' necessities after a surgical procedure will be determined to present the conceptual design of the system. These requirements will be incorporated in the mechanical design, which in conjunction with novel control strategies, are expected to make the robot an optimal solution for rehabilitation.

FIGURE 2.1: Main purposes for the rehabilitation improvement with the proposed novel robotic platform.

The principal aim of this dissertation is centered on developing a new robotic solution that helps to improve current gait rehabilitation in children with neurological or motor disorders as those derived from CP. Limitations of current RAGTs came from both low versatility offered by the robotic device and scarce definition of training protocols. In order to fulfil these limitations it is fundamental the understanding of four key ideas that will help to guide the process of development of the new robotic trainer covered in the framework of this thesis (see Figure 2.1):

- **Diagnosis:** The first step for the development of the new robotic device should be to understand the problem. An exhaustive study of the CP disease, risk factors, current limitations and patients' necessities for an appropriate recovery lay the foundations for the proposal of a new solution.
- **Research:** Once the principal requirements are detected, next step is focused on the research of new possibilities for improvement. The design of the robotic device (mechanical configuration and control strategies) will be based on the importance given to diverse selected features, also thinking in possible future therapies to be implemented with the rehabilitation platform.
- **Therapy:** After the prototype assembly, the definition of novel training protocols and its implementation in patients with CP should lead next stage to assess effectiveness with objective results.
- **Information:** Finally, these results should be returned to the people involved, specially clinicians and patients. Their judgement and concerns will serve to re-design activities carried out in previous points.

The ideas proposed in Figure 2.1 not only support the line followed in the thesis, but could also help to improve the assessments of current rehabilitation of patients with CP [43].

2.1 Users' requirements and layout

The requirements for the new robotic device must be obtained involving users throughout the whole design process. This philosophy of user-centered design was introduced in 1986 by Norman and Draper, and it requires the extraction of users' needs for a posterior validation of the designed product to the collected needs. The definition of the target population in this research was undertaken based on the conclusions of an expert panel discussion. Three different types of professionals comprised the expert panel: i) therapists, surgeons and other clinicians from the "Niño Jesús Hospital" (HNJ); ii) researchers from the "Biomechanical Institute of Valencia" (IBV); and iii) researchers and engineers from the "Neural and Cognitive Engineering group" (gNEC) of the "Spanish National Research Council" (CSIC).

The expert panel reached a consensus on defining a target population, which mainly comprised children with CP after a surgical process in their lower limbs. These representative users were selected because they were optimal candidates to test the new robotic platform, since they finished the critical growth phase and passed a surgical procedure that restored their lower limbs ameliorating musculoskeletal problems. 22 patients under this characteristic were studied in order to stablish the main rehabilitation requirements for pediatric population with CP. The mean age of the chosen population was 13.5±1.4 years-old and the mean weight 43.8±3.51 kg. All these patients had the necessity of correcting the stiff knee flexo through extensor bilateral osteotomies of distal femur. The gait pattern associated with these users was crouch gait, which is common in diplegic children with ambulation capability and individuals with tetraplegia who spend too much time in wheelchairs. The principal problems found after surgical processes in these children were:

- Limitation in motor control and associated spasticity.
- Muscular weakness.
- Increased energy consumption.
- A large period of rehabilitation up to 2 years.

Table 2.1: Descriptive parameters of the sample for interview

Sample composition	
Gender	- 9 females - 14 males
Age	- Users with CP aged 11 and 16 years-old - Relatives and professionals between 25 and 55 years-old
Classification	- 4 children with CP - 10 relatives - 4 doctors - 5 physiotherapists
Sessions description	
Duration	- Interviews: 1h - Discussion groups: 2h
Place	- Niño Jesús Hospital (Madrid) - AVAPACE Valencia - Biomechanical Institute of Valencia

The definition of the requirements for the new robotic trainer was based on the population problems exposed above, and the process included interviews not only with the expert panel groups, but also with users with CP and their families.

2.1.1 Discussion group and interviews

With the aim of collecting the principal requirements to incorporate in the new robotic platform, a discussion group was selected, which was composed by children with CP, their relatives and professionals as doctors or physiotherapists (see Table 2.1).

A discussion group is a group of individuals with similar interest who gather either formally or informally to bring up ideas, solve problems or give comments. It consists on a carefully planned conversation to obtain information about a specific field, in a permissive environment.

The election of the discussion group was complemented with interviews. An interview is a conversation between two or more people where questions are asked by the interviewer to elicit facts or statements from the interviewee. Interviews are a standard part of qualitative research, and seek to describe the meanings of central themes in the subject's life. It was considered as a method that helped to understand the experiences of others.

The goal of these discussion groups and interviews was to obtain exhaustive information about the necessities, interests and concerns of the target group with CP. Table 2.1

summarizes some descriptive parameters of the sample that composed the discussion group. The discussion group and interviews took into account the evaluation of current commercial walkers and their traditional rehabilitation. The participants in the symposium discussed about their own experiences with different models of walkers (posterior walker, anterior walker, walker with integrated seat...) and the physical rehabilitation carried out with their physiotherapists. Some requirements for the new robotic device were discussed based on their concerns.

2.1.2 Design requirements

The evaluation of the results derived from the discussion group and interviews provided some requirements, features and functionalities that should be integrated in the novel device. Focusing on the demands to cover by the new robotic platform, this section distinguishes different points that are separated in several fields: i) the correction of problems related to gait function; ii) posture and balance, iii) clinical aspects that the robotic device needs to fulfil; and iv) other important general characteristics. Figure 2.2 represents in a schematic way all the selected features grouped in the four fields and the relative importance provided by the users of the discussion group.

The most voted desire was to change the patient's previous gait pattern (Figure 2.2). It means to improve the traditional rehabilitation through the new robotic device in order to relearn to walk. Covered by this first requirement, there were other three characteristics that also received high importance, and they looked for rehabilitation from over-ground walking, relearning from verticality and including also the upper body (trunk posture).

Other requirement with great significance for the clinicians was the "Assist-As-Needed" (AAN) strategy, which allows individual and selective support for all the joints. In the same level of importance was the PBWS, which has to be highlighted because the existing over-ground gait trainers do not offer this possibility. Also the safety of the device, which should be understood as the prevention of falling.

After these principal concerns, some other requirements took more or less the same importance. They were mainly related to ease of use, comfort, versatility and how the new device could reduce the therapists' effort in the exercises. The remaining requirements were in most cases covered by the ones afore indicated or had lesser relevance.

These conclusions served as the base to design the concept of the new rehabilitation device. To address the proposed requirements, next section covers the introduction to

FIGURE 2.2: Requirements for the new concept of robotic gait trainer and their relative importance given by the people involved in the discussion group.

the conceptual design of the novel robotic platform for gait rehabilitation and training in patients with CP and analogous disorders. This platform is named CPWalker.

2.2 Robotic platform for gait rehabilitation and training in children with CP

This section is oriented to give an analysis of human gait linked to the preliminary conceptual design of the new robotic platform for gait rehabilitation: CPWalker. The ambition with the new device is to provide novel robot-based therapies to enhance walking function in children with CP.

2.2.1 Biomechanics of human walking

To specify the structure of the new device and prior to start with the the mechanical design of the rehabilitation equipment, it was necessary to understand the biomechanics of human walking as an essential part for developing such robotic device. The analysis of normal gait will served to define the DOFs in which CPWalker robotic platform should provide assistance.

The process of human walking starts with an impulse in the CNS and concludes with the emergence of reaction forces on the ground. A gait cycle is the period of time between a first foot ground contact and the next ground contact by the same foot. Each gait cycle is commonly classified in two main phases: stance phase and swing phase, both represented in Figure 2.3. Focusing the attention on right leg (blue shadow leg on Figure 2.3), the stance phase comprehends the period in which right foot is in contact with the ground (around 60% of the whole cycle), being the swing phase the time in which the right foot is elevated preparing the next heel strike.

Foot prepositioning is the first subtask in the gait cycle (Figure 2.3) [91]. It means preparing the knee extension and hip flexion to support a good weight acceptance. Once the contralateral foot is lifted of the ground, all the weight is supported by a single limb, so it is necessary to maintain the stability during this stance phase. The shift from stance to swing is preceded by the push off subtask, where the ipsilateral foot takes off the ground. In this moment is very important to keep enough distance from the floor executing a proper step height (foot clearance in Figure 2.3). The swing phase ends ensuring that the step length is adequate to start again a new gait cycle.

The sagittal plane is the dominant plane of motion during human walking. The movements referred to this plane are flexion (the limb approaches the body) and extension

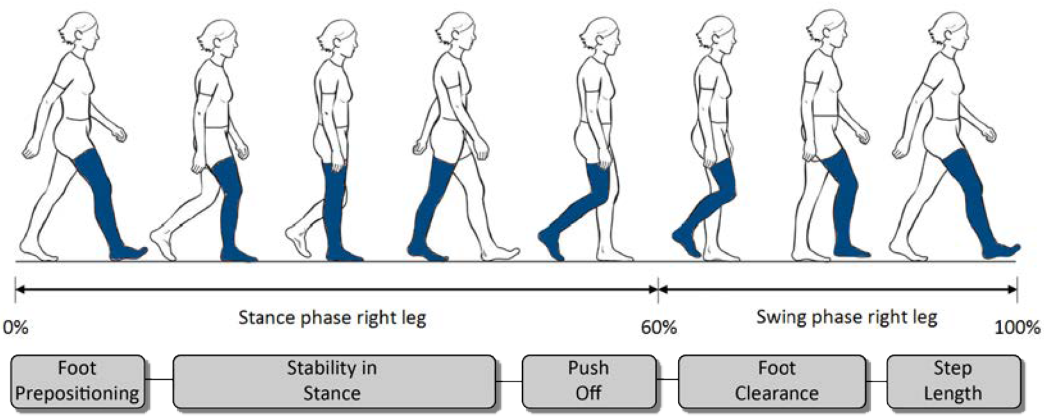


FIGURE 2.3: Gait cycle diagram and gait subtasks (grey blocks) focused on right stride.

TABLE 2.2: Estimated power for human flexion-extension movements during normal walking

Joint	Flexion Power [W/kg]	Extension Power [W/kg]
Hip	0.93	-0.57
Knee	0.73	-1.12
Ankle	3.21	-0.42

(the limb is away from the body) for all the joints of the lower limbs. Table 2.2 shows the estimated power of each joint for human walking in sagittal plane [92].

2.2.2 Conceptual design of CPWalker

The conceptual design of CPWalker aims to solve the limitations found on the current commercial rehabilitation robots. Concretely, CPWalker will integrate in only one platform all the advantages collected from commercial rehabilitation equipments for CP, introducing improvements to address the challenges proposed for these robotic devices (see Table 2.3).

To justify the different fields of Table 2.3, there are some studies [42, 61, 87, 88] that demonstrate promising results of robotic strategies for gait rehabilitation related to improvements on patients' kinematics, speed and ambulation endurance. On the other hand, the provision of PBWS in robot-based therapies is beneficial in case of children

TABLE 2.3: Main aspects and principal advantages of current robotic devices for gait rehabilitation in CP

	Actuated and Guided Movement	PBWS	Over-ground Training	Central Nervous System	Peripheral Nervous System	Active Postural Control	Task Specific Training
Innowalk	*				*		
Innowalk-Pro	*				*		
NF-Walker			*	*	*		
Lokomat	*	*			*		
GT-1 RehaStim	*	*			*		
Walkbot	*	*			*		
Autoambulator	*	*			*		
Multi-robot				*	*		
CPWalker	*****	*****	*****	*****	*****	*****	*****

with a severe level of disability (GMFCS III, IV and V) [49, 50, 93, 94]. Nevertheless, these new therapies should not replace over-ground treatments [95]. The possibility of free over-ground displacement in real rehabilitation environments and the inclusion of CNS and PNS into the treatment, encourage more challenging exercises with an important motivating condition and, as a consequence, a proper physical rehabilitation. At the same time, to maintain a correct posture during walking is a very relevant aspect in case of children with CP [96, 97]. The inclusion of different sensors to improve postural control during robot-based therapy is expected to lead to better treatment results. Finally, the option of implementing strategies focused on specific and selected subtasks of walking has been demonstrated to be a crucial factor in facilitating functional improvements [84, 98].

Figure 2.4 shows an overview of the preliminary concept of the CPWalker robotic platform. This concept looks for improving the users' physical and cognitive skills by involving the requirements of Table 2.3. The device is composed by two main parts: a walker to provide balance and support to the patients during over-ground walking training, and an exoskeleton to guide the joints of their lower limbs allowing flexion and extension movements in sagittal plane. Several sensors were distributed throughout the platform constituting the MHRI for the interaction between the patient and the robot. These sensors were the foundation for the inclusion of CNS and the implementation of task specific training through AAN strategies. The concept of CPWalker (Figure 2.4) introduced a new change on the rehabilitation treatments, which was focused on four main pillars: first, the possibility of free over-ground movement with PBWS (not restricted to treadmill training) in rehabilitation environment, which could be an important motivating condition for this population; second, the use of AAN strategies in specific subtasks of walking might optimize the treatment by increasing the active patient's participation; third, the inclusion of different sensors to carry out novel strategies as the improvement of postural control of head and trunk during robot-based therapy, was expected to provide progressions of the child's gait patterns; and finally, the integration of CNS was expected to boost the effects of the therapy.

The new trainer promotes the progression of patients with CP into the rehabilitation therapy, increasing the level of intensity and frequency of the exercises as well as enhancing the motivation and tailoring the therapy to each user. CPWalker is the first trainer with PBWS and active driven gait in over-ground environments, a platform with an interface that corrects the child's posture while participating in robot-based therapies, and a device which includes PNS and CNS into the treatment through the incorporation of different technologies [99]. Overall, CPWalker provides the child with a structure that rehabilitates their gait to physiological patterns.

FIGURE 2.4: Overview of CPWalker concept.

Following sections describe in depth the mechanical design of CPWalker, each active system, their justifications, re-designs and the control architecture of the project.

2.3 Mechanical design of CPWalker

In order to define the mechanical design of the robot, some priority DOFs were selected based on the conclusions derived from the gait cycle analysis (section 2.2.1). At the beginning, hip, knee and ankle flexion/extension were required to be powered. Nevertheless, the active ankles were unnecessary after few preliminary tests with real pediatric patients, due to children with CP usually use AFOs, so the movements of their ankle joints are limited. On the other hand, pelvis movements could became important if an unrestricted walking is desired. However, in this case of rehabilitation and taking into account their complexity, pelvis movements were not assigned that importance (only pelvis up/down is powered on CPWalker). Requirements for hip abduction/adduction were constrained to prevent children walking with inadequate step width. Table 2.4 summarizes the prioritized DOFs in CPWalker.

With the selected DOFs in mind, CPWalker robotic platform was built based on the commercially available device NF-Walker (Made for Movement, Norway). This decision was taken as a consensus after talking to families and clinician partners, because the existing passive device NF-Walker was familiar for most of them, and additionally, it was an ideal base structure to provide the required compensation for our project. The conceptual design of CPWalker incorporated mechanical modifications on the NF-Walker in order to transform this passive device into an active rehabilitation robotic platform.

Concretely, the intention was to design a fully active rehabilitation device, which besides providing guided movement for the lower limbs, it also enabled the clinicians to implement robot-based therapies including strategies of postural control and allowing free displacement through real rehabilitation environments. In order to do so, four active systems were incorporated: i) a drive system of the platform; ii) a PBWS system; iii) an active system for the adaptation of hip height; and iv) a system for controlling joints motion in the exoskeleton. Figure 2.5 presents a parametric CAD model of CPWalker, which was developed as the base of the conceptual design. This 3D system includes the mechanical adaptations of the NF-Walker and most of the necessities required by the discussion group. The aid of IBV was very important to design a preliminary version of the mechanical modifications implemented on the NF-Walker. In this regard, some actuators requirements were defined based on previous work [100].

At a more detailed level, the information derived from the interviews with professionals and real patients concluded that the maximal walking speed should be 0.6 m/s to achieve a safe rehabilitation with the target patients. The robotic device should be able to accommodate the anatomical measures of the population: children with CP aged among 11 and 18 years old, which dictates the wearer height and hip width. These data were retrieved from population with CP recruited at HNJ. Likewise, the maximum weight the robotic platform should support was 80 kg. As the weight of the robotic platform is not supported by the user, but discharged through the own device, it was not a constraint for the design.

Table 2.4: Prioritized DOFs in CPWalker platform. The type of actuation might be: powered (P), free (F), or constrained (C)

DOF	Type
Pelvis up/down	P
Pelvis transversal rotation	C
Pelvis frontal rotation	C
Pelvis anterior/posterior tilt	C
Hip flexion/extension	P
Hip abduction/adduction	C
Hip internal/external rotation	C
Knee flexion/extension	P
Ankle plantar/dorsiflexion	F
Ankle inversion/eversion	C

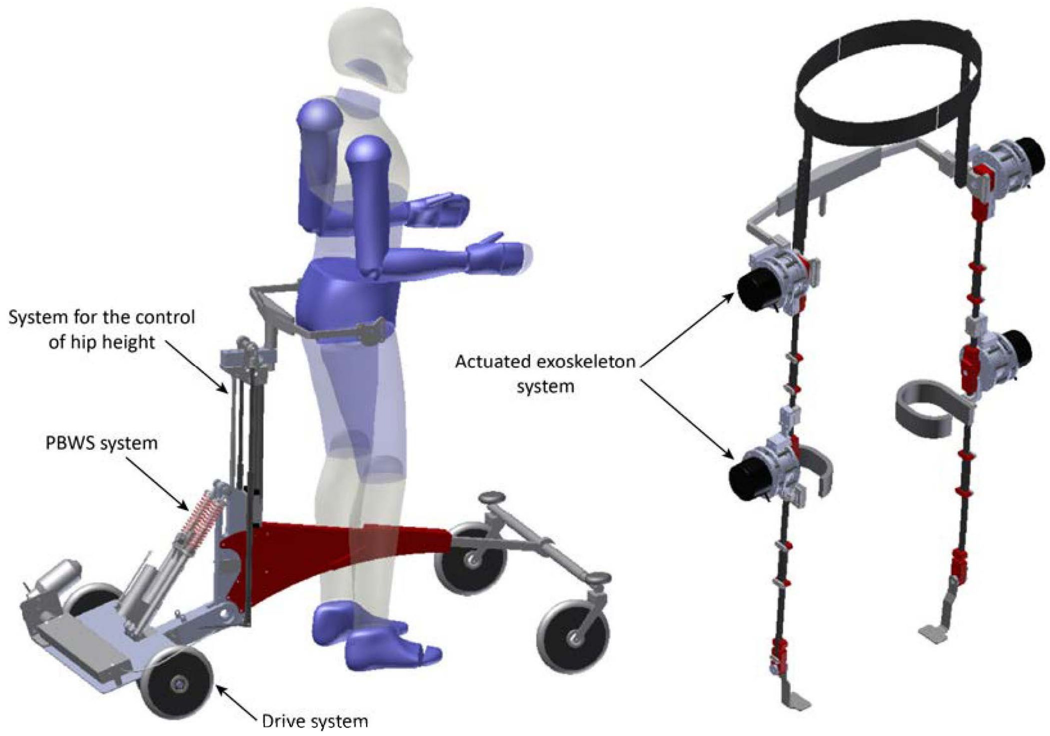


FIGURE 2.5: Parametric CAD model of CPWalker: smart walker and exoskeleton.

2.3.1 Smart Walker

In the field of the robotic assistance for gait rehabilitation, the robotic version of walkers, known as "smart walkers", has been developed during the past decades. A smart walker is a robotic device which provides assistance to the user using different levels, depending of the patient's needs [52]. The purpose of the smart walkers is to interface with the user's residual neuromusculoskeletal structures such that physical support, sensory or cognitive assistance are reconnected [101]. A remarkable example of smart walker is the PAMM system (Personal Aids for Mobility and Monitoring) [102], and GUIDO system, a smart walker for people with visual impairment and cognitive deficit [103]. On the other hand, the project SIMBIOSIS, from Bioengineering Group (CSIC) [104], introduced the implementation of a robotic smart walker designed to help people with reduced mobility through an adaptive control of the user's residual capability. Recently, new types of smart walkers have appeared with the same purpose [105].

The smart walker of CPWalker supports the patient with CP during over-ground rehabilitation. Its structure was complemented with three of the abovementioned actuated systems: i) drive system; ii) PBWS system; and iii) system for the adaptation of hip height. These systems, their actuators and sensors are described in the next points.

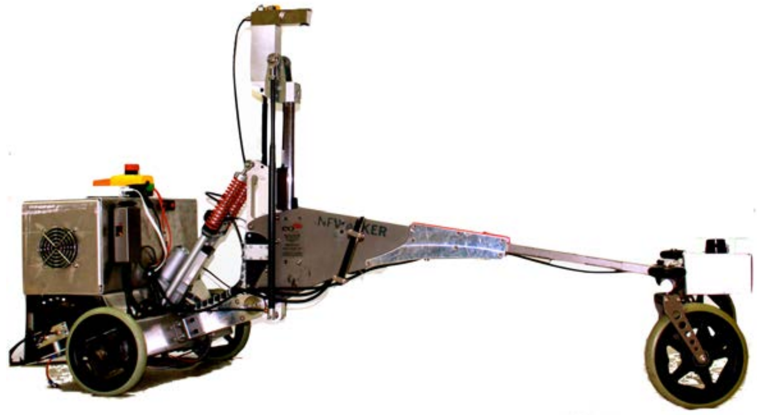


FIGURE 2.6: Smart Walker structure of CPWalker.

2.3.1.1 Structure

The structure of the walker of CPWalker is represented in Figure 2.6. It is responsible of supporting the child's weight during gait, and provide the required balance. The walker structure rests on four wheels (two of them in the front side and the other two in the back). The front wheels are passive, being the traction system located in the back wheels. The main function of the front wheels is to allow turns of the platform in case of curved trajectories.

The structure of the smart walker may resist a total maximum weight (exoskeleton + patient) of 80 kg as it was defined in the prerequisites. Assuming the weight of the exoskeleton up to 5 kg, the maximum weight of the user should not be more than 75 kg.

2.3.1.2 Drive system

The drive system was located on the back wheels, and it provides the translation movement required to achieve the necessary support for an over-ground treatment instead of the ambulation on a treadmill (Figure 2.7). This system is composed by the following components:

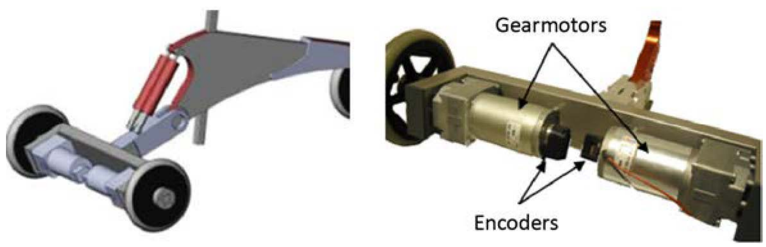


FIGURE 2.7: Drive system of CPWalker platform.

Actuators: The drive system is constituted by two gearmotors of 24 Vcc and 50 W, K80 63.105 (Kelvin, Spain) [106] coupled to each rear wheel. Motors work individually, providing independent speed to left and right wheels. This characteristic allowed the possibility of achieving turn displacements of the platform by providing different speeds of each wheel. The speed range of the device was encompassed between [-0.60, +0.60] m/s, being dependent on the diameter of the rear wheels (0.17 m).

Sensors: Two rotatory encoders were installed (HEDS-5540), one for each traction engine. A rotary encoder, also called a shaft encoder, is an electromechanical device that converts the angular position or motion of a shaft to an analogical or digital code. Information provided by the encoders is used to control the velocity of the walker traction [12, 99].

2.3.1.3 Partial body weight support system

The PBWS system (Figure 2.8) is responsible for the control of the user's body weight discharge. The ability of discharging a partial user's weight during gait, improves the patients' rehabilitation because they have to use less activity to neutralize the gravity and, thereby, can take advantage of their residual force to learn and coordinate movements [107]. It aimed at making easier the exercises along the first sessions (when the patient is weaker) or with users with a greater GMFCS score [49, 94]. In CPWalker, user's weight is supported by a harness linked to the exoskeleton that attaches user's trunk and pelvis. Thereby, the total weight (user + exoskeleton) is discharged throughout the platform. The actuators and sensors of this system are:

FIGURE 2.8: System for the control of user's weight.

Actuators: The PBWS system consists of an electric linear actuator CAHB-10-B5A-050192-AAAP0A-000 (SKF, Sweden) [108], which with an input voltage of 24 Vcc can achieve 1000 N of load. Its stroke length is 50 mm, and concretely, this model has a potentiometer inside. The actuator compresses and decompresses the original springs of NF-Walker (Figure 2.8 left), and therefore user's weight is controlled by this compression and decompression. It allows a significant unloading respect to the ground up to 45 kg. The weight discharge will be from 0% (user is completely rested on the floor) to 100% (user is suspended).

Sensors: The sensory part of the PBWS system is composed by a potentiometer and a load cell:

- Potentiometer: the elevation system is equipped with one potentiometer, which measures the compression or decompression of the springs of the suspension system, being located between them (Figure 2.8 right). This measure is used to implement the fine control of the user's weight discharge.
- Load cell (AEP FT1 C2 class): this force sensor was integrated into the walker structure (Figure 2.8 right) in order to measure the amount of user's weight that is supported by the robotic platform. This information is therefore used for the control system.

2.3.1.4 System for the adaptation of hip height

This system is primarily used to adapt the robotic platform to different anthropometric users' sizes by adjusting the hip joint of the exoskeleton at a specific distance from the ground (Figure 2.9). The system is able to elevate the patients from the floor and position them with legs stretched. Therefore, the user can walk without restrictions. Additionally, this system is also part of the PBWS system, and allows the compensation of hip movements during walking. After few tests with patients, author concluded that if the static calibration of PBWS was performed correctly through the hip height adaptation system, the support of the previous actuator (presented for the PBWS system) loses importance during walking. This fact implied the simply use of the load cell at the same time than the system for the adaptation of hip height, to implement the statical calibration. Subsequently, the active control of PBWS may be continuously generated by the adaptation of hip height during walking, since this system is faster than the previous one. To perform such actions, the system is composed by the following actuators and sensors:

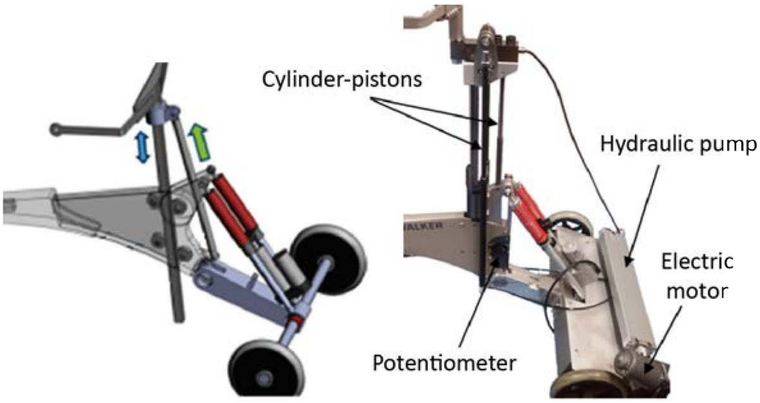


FIGURE 2.9: System for the control of hip height.

Actuators: The system for the control of hip height is activated by a linear actuator E21BX300-U-001 (Bansbach easylift, Germany) [109] composed by a hydraulic pump and two cylinder-pistons. The hydraulic pump is controlled by an electric motor. The pistons are connected to the hip joint of the robot and their displacement is supported by a rail linked to a slim-line carriage (LLTHR 20 D4 405 and LLTHC 20 LR T0, respectively, (SKF, Sweden)). The system can control the height of the user's hip in relation to the ground (Figure 2.9). With a stroke length of 300 mm, this actuator is able to generate forces high enough to elevate the child. The cylinders work in parallel through a slideway that supports the bending moments generated by the user's weight.

Sensors: This system has one potentiometer for the height regulation system (WS31-500-R1K), which is located in the docking between the exoskeleton and the walker (Figure 2.9). This potentiometer changes the measurement according to the hip elevation with respect to the walker platform. This parameter gives information about the position of the hydraulic linear actuator (maximum and minimum height). For security reasons, these extremes (maximum and minimum) are controlled both via software (using the information of the potentiometer) and via hardware through mechanical end-stops.

2.3.2 Exoskeleton

Exoskeletons are wearable devices with a kinematic configuration similar to the human body, which have the ability of implementing guided and repetitive movements to the user's extremities [110]. The word exoskeleton comes from Greek *éxō* that means "outer" and *skeletos* "skeleton", thus it is designed with the aim of supporting and protecting human body from the outside. Work with exoskeletons began in the early 1960s, but only recently these devices have been applied in rehabilitation of patients suffering from motor disorders. Repeatability allows exoskeletons to perform more intensive rehabilitation

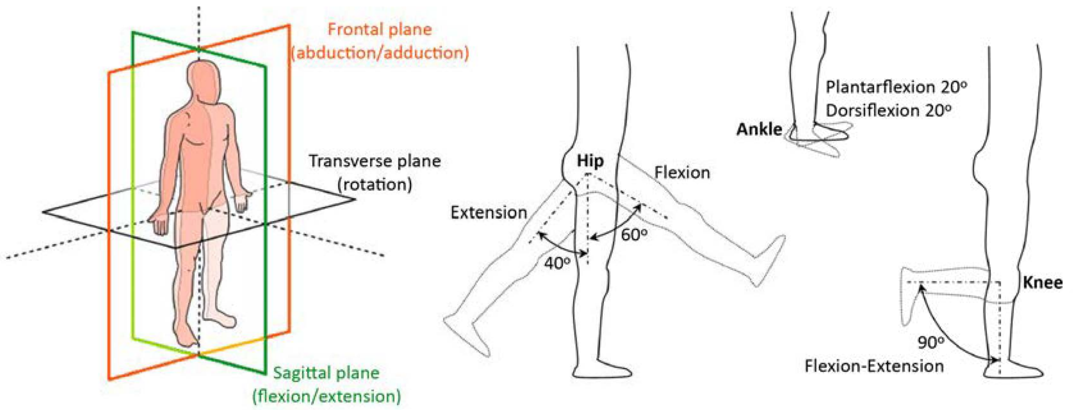


Figure 2.10: Anatomical planes and displacement ranges allowed by the exoskeleton of CPWalker.

training than that done by conventional manually therapy, so it accelerates the function recovery [111].

The exoskeleton of CPWalker was designed to guide user's lower limbs in sagittal plane with 6-DOFs (bilateral actuated hip and knee, and free ankle), remember Table 2.4. The six joints may be adjusted following different requirements depending on the application. In that way, the exoskeleton of CPWalker was defined as a modular lower limb exoskeleton. The provided displacement ranges plenty satisfies the normal gait patterns in sagittal plane [112]. These ranges were used as maximum boundaries for safety reasons (represented in Figure 2.10).

2.3.2.1 Structure

The structure of the exoskeleton of CPWalker fulfils a set of functional roles including patient's support and protection. At the beginning, this structure was based on the original NF-Walker device, but later author figured out that these original rods were not strong enough to withstand the torque provided by the actuators. As a result, a new structure was designed, in which the requirements of actuators were maintained from previous design. Aluminium 7075 was mainly used in the structure of the exoskeleton and joints, due to its mechanical resistance and lightweight. The whole design of the exoskeleton is lightweight and, at the same time, rigid and strong in order to allow walking and increase strength and endurance of people with mobility disorders, in particular children with CP. As consequence, the structure is hard enough to support its own weight and the user's weight, as well as torsional stresses produced by patient's movements.

The joints of the exoskeleton correspond to the joints of human body, it means, hip, knee and ankle. The design of these actuated joints was developed with the aid of IBV.

Figure 2.11: Range of measures of CPWalker exoskeleton.

The structure of the exoskeleton must maintain the joint alignment in patient's lower limbs, provide movement assistance in sagittal plane, increase the coordination of the tasks and prevent restrictions to the natural movement as far as possible. The rotation and abduction/adduction movements are restricted in this system with the intention of preventing the children get used to walk with legs spread wide (see also Table 2.4).

In order to make the robot compatible with different users, the length of the structure can be adjusted to different patient's anthropometric measures. The allowed range of anthropometric measures is shown in Figure 2.11. Adjustable mechanisms, such as telescopic structures in the thigh and shank and a sliding rail system in the pelvis, are used to accommodate inter-subject anatomy diversities.

Besides the adjustment to different anthropometric measures, the joints of exoskeleton must adapt to the patients' mobility and follow their movements. In addition, the exoskeleton prevents displacements of lower limbs to abnormal positions. The device has been designed for over-ground walking training, and according to this, the maximum allowed range during walking is: 60º for hip flexion, 40º for hip extension, 90º for knee flexion and 0º for knee extension (Figure 2.10), which is in accordance with [112]. The movable range ensures the necessary motion for proper gait rehabilitation. For safety reasons, the range limitation is kept by both hardware (adjustable end-stops) and software.

The exoskeleton is attached to the human body through three straps for each leg (one on the thigh and two disposed on the shank). This attachment allows the distribution of forces along all the implicated body segments. Finally, the exoskeleton of CPWalker is linked to the smart walker through a held coupling, which blocks its liberation and allows the possibility of PBWS.

2.3.2.2 Exoskeleton joints system

The exoskeleton joints system is the most complex system of CPWalker platform (see Figure 2.12). As previously exposed, it is composed by six joints responsible for the control of the patient's lower-limbs (hips and knees are actuated and the ankles may move freely). The goal of this active system was to guide the user's lower limbs with a predefined range of motion (ROM) accepted by the clinicians. The combination of diverse configurations related to the number of allowed DOFs (Table 2.4), gave a desirable modularity to the device, which was a required factor in order to adapt the treatment to the patient's progression. The system is composed by the actuators and sensors described below.

Actuators: The actuation of each exoskeleton joint is composed by a harmonic drive CSD-20-160-2AGR (Harmonic Drive LLC, USA) [113] coupled to a brushless flat DC motor EC-60 flat 408057 (Maxon ag, Switzerland) [114].

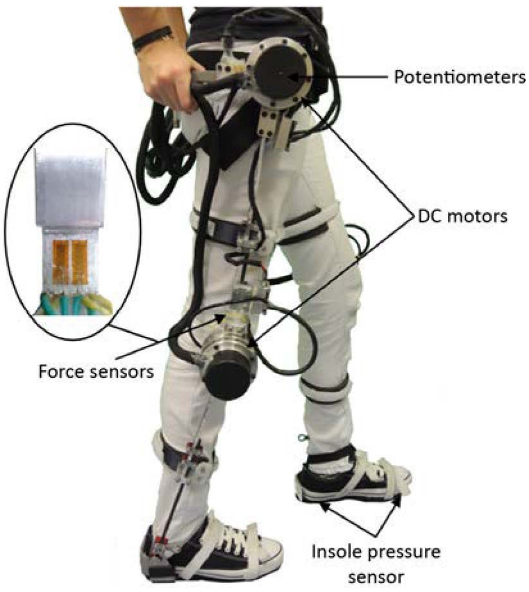


FIGURE 2.12: User wearing the exoskeleton system.

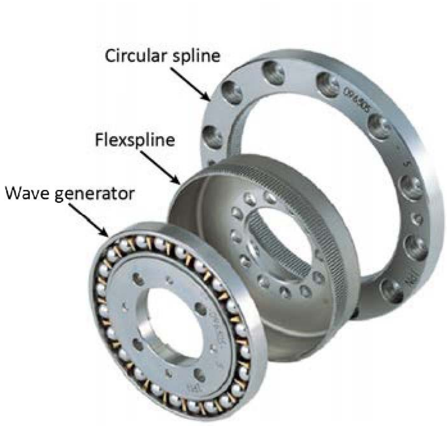


FIGURE 2.13: Harmonic drive exploded view.

The actuation with DC motors has the main advantage of being controlled with moderated voltages and their response is fast. The energetic efficiency for these types of actuators is good, and they behave linearly. The principal problem is that they are noisy when working, specially if they are combined with reduction ensembles. The brushless option was chosen due to brushless motors are smaller than brush ones for the same power. Moreover, the maintenance for brushless motors is easier. The main characteristics of the three-phase DC motor [114] of the exoskeleton joints are: maximum speed of 6000 rpm, 100 W of power, nominal voltage of 24 V and a weight of 470 g.

The harmonic drive mechanism (Figure 2.13) was selected due to its capacity of working with high gear reduction ratios, allowing ensemble position accuracy with a low weigh/volume ratio [115]. The strain wave gearing theory is based on elastic dynamics and utilizes the flexibility of metal. The mechanism has three basic components: i) a wave generator located inside the mechanism and where the ball bearing is situated; ii) a flex spline that is like a shallow cup. It fits tightly over the wave generator and has external teeth positioned around its; and iii) a circular spline, a rigid circular ring with internal teeth. The flex spline is placed inside the circular spline meshing their teeth. The selected harmonic drive has a rated torque of 28 N·m at 2000 rpm, limit for momentary peak torque of 76 N·m, maximum input speed of 10000 rpm and positioning accuracy of $2.9 \cdot 10^{-4}$ rad.

The gear transmission of the whole joint is 1:160. This setup was adopted since it allowed the design of a compact actuation system [116]. The assembly provides an average torque of 35 N·m, which is in accordance with the requirements of [117, 118].

Sensors: The transmission of information related to the sensors of the exoskeleton was carried out through two signal wires. This characteristic is highly favourable because

FIGURE 2.14: Simulated deformation in the rods of the exoskeleton of CPWalker when a force of 20 N is applied on the extreme. The finite methods calculation defines the proper position of the selected strain gauges (R1, R2, R3 and R4), which is the zone that suffers more efforts (light blue and green).

the converters used to transmit the information of the joints are disposed keeping a linear distribution. The exoskeleton system is equipped with the following sensors:

- Potentiometers: the exoskeleton has one potentiometer placed on each joint assembly (bilateral hip and knee). In the first design of the joint, each potentiometer was coaxial with the axis of the joint and embedded in the centre of the assembly. This location provided a more secure and robust connection. Nevertheless, after several tests with patients, this position was changed due to its poor accessibility. Nowadays, the potentiometers are located outside the joints, connected to the axis through a pulley-belt system. Voltages values received from these potentiometers are converted to angle values, which provide information of the angular position of each joint. The model of the potentiometer is Vishay model 157 [119], with a range of resistance between 1 kΩ to 100 kΩ.

- Force sensors: force sensors based on strain gauges were located in the metal rods of the exoskeleton, which are coupled to the joints. These sensors are responsible for the measurement of the interaction forces between the robot and human body. The strain gauges are electrical resistors fixed to the structure, and as consequence of application of forces in the structure, these are transmitted to the gauge, resulting variations in the electric resistors. Strain gauges are connected in a Wheatstone bridge circuit with a combination of four active gauges (complete bridge), which allows the possibility of achieving higher sensitivity [120].

  The strain gauges selected for this project are uniaxial resistors of 120 Ω each, with a contact surface of $5 \cdot 1.8$ mm^2 (Figure 2.14 (a)). These parameters were chosen according to the main effort to be measured (sagittal direction) and because they provided a better heat dissipation than smaller sizes. The position of the strain gauges in the exoskeleton of CPWalker is represented by Figure 2.14. The Wheatstone bridge was built on the surface of the rods that is perpendicular to the rotation radio. Thereby, the effects of forces in other directions were reduced.

To calibrate the strain gauges in the Wheatstone bridge, each segment of the robotic leg (thigh and shank) was fixed in horizontal position. Subsequently, some calibrated masses of known weight were added to the opposite extreme from the gauges location in order to take into account the highest torque. Concretely, author chose a distance of 10 cm from the gauges to normalize the calibration for all the joints.

The information provided by the force sensors will be used to implement different control strategies as impedance or force controllers. These sensors allow the possibility of applying the AAN philosophy in order to take advantage of user's residual movement.

- Insole Pressure sensor: a force-sensing resistor (FSR) is a component whose resistance changes when a force or pressure is applied. CPWalker uses two FSR^{TM} 406 (Interlink Electronics, United States) for each insole (one for the heel and other for the tiptoe). These sensors provide information related to the user's footsteps, which is useful to assess the patient's gait pattern.

2.4 Control Architecture

Once the mechanical design of the device has been presented, it is time to describe how the interaction of the platform was performed. The control architecture of CPWalker, represented in Figure 2.15, is basically composed by three main components:

- **Clinician interface:** consists of a tablet device that executes an application developed for the interface between the system and the doctor who is using it. Through this interface, the practitioner may configure the therapy, evaluate it in real-time and save the necessary information. This unit will be presented in chapter 3 after the definition of the control strategies in order to give a complete version of CPWalker project.

- **Control unit:** responsible for acquiring information from the different sensors of the robotic platform, executing the algorithms for the implementation of the therapies in real-time, and generating the control signals for the actuators. Following sections analyse this unit in more detail.

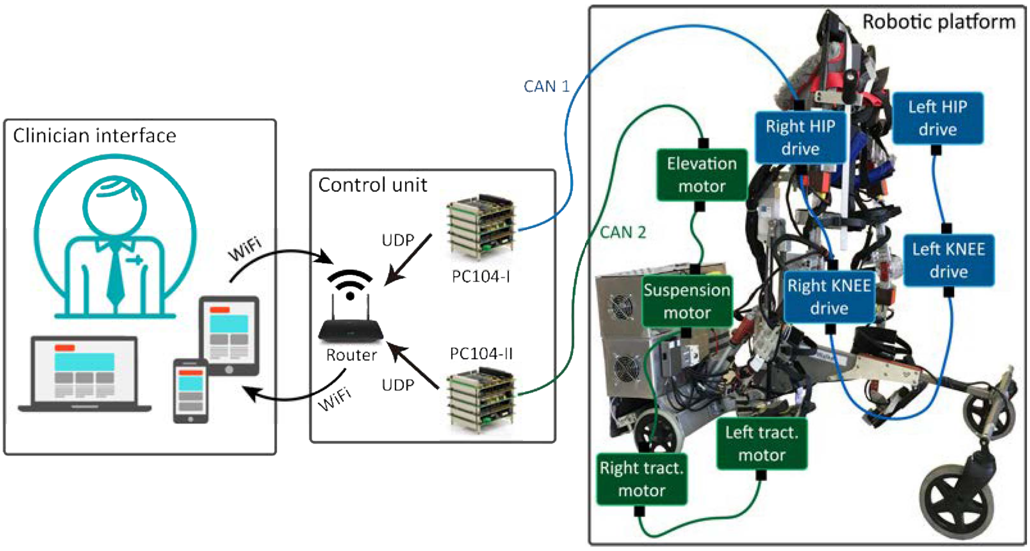


FIGURE 2.15: CPWalker overall control architecture: clinician interface, control unit and robotic platform. All sensors in both exoskeleton legs communicate to PC104-I through a CAN bus (deterministic real-time) network (CAN1). Motor drivers of the exoskeleton are connected to a D/A board of the PC104-I. PC104-II is responsible for the control of the traction and body-weight support systems. Drivers for controlling the motors of these systems and for reading their sensors are communicated with PC104-II via another CAN bus (CAN2). PC104-I and PC104-II together constitute the control unit of CPWalker platform. Both PC104 systems are connected to a WiFi hub that enables the communication of both controllers with an external device or tablet that executes the clinician interface and allows clinicians to access information of CPWalker and to control it.

- **Robotic platform:** constituted by the exoskeleton and the smart walker with their structure, sensors and actuators, as described in section 2.3.

The control architecture combines the control algorithms with the robotic platform. It had two main functions: i) to obtain the signals that are necessary for the control, data analysis and evaluation (position angles, velocities, forces...); ii) to generate the control signals that activate the actuation systems. The communication between the components of the control architecture is illustrated in Figure 2.15, and it is based on the architecture of [121]. The communication protocol between the sensors and the control unit is CAN bus (Controller Area Network), which is a standard vehicle bus designed to allow microcontrollers and other devices to communicate with each other without a host computer [122]. This communication topology was chosen due to its facility for the transmission of messages. With CAN bus, the volume, complexity and difficulty of communication were reduced. With the aim of reading the messages, CAN converters are distributed throughout the whole platform. Each CAN converter has one identifier associated, which enabled the main controller to distinguish between them [123]. Meanwhile, the communication among clinician and control units is performed through Ethernet-UDP and WiFi. UDP uses a simple connectionless transmission model with a minimum of protocol mechanism.

2.4.1 Control unit

The control unit was composed by two PC104, one responsible for the control of the smart walker, and the other responsible for the exoskeleton. PC104 is a family of standard embedded computers, which defines both form factors and computer buses [124]. The control of the entire robotic platform is implemented into MatLab real-time environment. This environment enables the development of mathematically complex control strategies in real-time. The two PC104s communicate with the different sensors of the platform through CAN bus (1 Mbps). The communication with the exoskeleton is done through PC104-I with "CAN bus 1", and the smart walker follows PC104-II with "CAN bus 2" (see Figure 2.15). On the other hand, both PC104s are connected between them through Ethernet-UDP. As consequence, they can send messages to each other without any additional device. The boards of PC104s are stacked on top of each other like building blocks. In case of CPWalker, both PC104s have four stacked modules that from bottom to top they are:

- **Power supply (PCM-3910-00A1E):** responsible of providing electrical current to several circuitries of the control unit. The PC104 is powered with 24 V, and internally it can supply voltages of ± 12 V and ± 5 V to provide energy to other external devices besides the control unit.
- **Central Processing Unit (PCM-4153F-L0A2E):** ADM Geode^{TM} LX800 500 MHz is the electronic circuitry within the central unit that carries out the instructions of a computer program by performing the basic arithmetic, logical, control and input/output operations specified by the algorithms.
- **CAN board (CAN-AC2-104):** which is used with the aim of establishing the communication protocol based on bus topology for the transmission of messages. Each PC104 has two independent CAN bus located on the CAN board, and the transmission can achieve 1 Mbps.
- **Data acquisition board (DMM-32-AT):** the control unit is also equipped with an acquisition module for the interface between the actuators and the controller. The selected target is DMM-32-AT (Diamond System Corporation, United States) [125], which measures data from the real world and converts the resulting samples into digital values that can be manipulated by a computer. It is composed by: 32

Figure 2.16: Communication architecture between control unit and both systems: exoskeleton and walker. Dotted lines indicate CAN bus signals and solid lines indicate analog signals.

analog inputs (16 differentials) with a resolution of 16 bits, and 4 analog outputs with a resolution of 12 bits and sample rate of 200 kHz.

The PC104s are responsible for transferring the control orders from the user's interface to the control drivers, which are the ones that command both the exoskeleton and the smart walker. This communication is represented by solid lines in Figure 2.16. Likewise, the PC104s receive information from the sensors of the whole platform via CAN bus (dotted lines in Figure 2.16).

The drivers were selected individually and carefully for each system of CPWalker. In consequence, with the aim of reading the information from the different sensors, CPWalker uses CAN converters based on [121]. The exoskeleton has one CAN converter for each joint (six in total), which are responsible for acquiring position and force measured on the joints by the potentiometers and the strain gauges respectively, and the pressure on the FSR located on the insoles. Meanwhile, the smart walker uses four CAN converters: two converters for the drive system, one for the PBWS system and one for the control of hip height system. They send the measures of the potentiometers, encoders and weight gauge to the corresponding PC104 via CAN bus.

The drivers that produce the control signals to command the motors, are commercial devices. Specifically, the drivers used to control the brushless DC-motors of the exoskeleton have the reference AZBH12A8 (Advanced Motion Control, United States). Meanwhile, the smart walker presents two control drivers: one driver is capable of controlling both traction motors and a second driver that controls the system for the hip height and the PBWS system. These commercial drivers have the reference MD22, with dual channel and an output current of 5 A for each channel.

Finally, the control algorithms of the platform are developed in Simulink, which is a graphical extension of MatLab that uses block diagram environment for model-based design. The Simulink models are built by MatLab Real-Time Workshop [126], which generates and executes C and C++ code from Simulink. The generated source code is used for real-time applications in any compatible computer. In this process, xPC Target is involved, which is a host-target PC solution for prototyping and testing real-time systems.

The communication cycles of the system occur at a fixed rate (1 kHz) set by the control scheme on the control unit. As a result, this protocol allows for deterministic control and it provides built-in network error detection as, for every message received, each system has to return data information to the control unit. For safety reasons, the control architecture and thereby, the control unit, have an emergency button that instantly shuts down the power of the robotic platform if any failure occurs on the network.

2.5 Conclusions

This chapter presented the design and development of a robotic platform for gait rehabilitation of children with CP and related motor disorders. Before to start with the design of the robotic device, the patients' necessities were identified, as well as the principal demands to cover by the new system. These requirements were selected based on user-centered decisions, involving pediatric patients and relatives throughout the whole design process.

The final mechanical design of the smart walker and the exoskeleton took into account the conclusions of an expert panel comprised by engineers, clinicians and researches. CPWalker robotic platform incorporates several systems that will allow the implementation of different and novel control strategies to address the limitations of current rehabilitation devices for CP.

Finally, the chapter defined the control architecture of the whole platform. The interaction between the components of CPWalker was mainly carried out by WiFi and UDP protocol. The most important part was the control unit, responsible of processing the control signals. This unit will also holds the control algorithms created with Simulink.

Next chapter will introduce the MHRI of CPWalker and its components. Some of the technologies of the MHRI will be used to develop diverse control strategies at high, mid and low levels, which will be the support of therapies carried out with the robot.

Subsequently, and following several elemental control strategies, a preliminary clinical protocol will be proposed taking advantage from all the possibilities of CPWalker.

Chapter 3

Development and Preliminary Validation of Robot-Based Rehabilitation Therapies with CPWalker Platform

Current robotic systems have the advantage of inducing movements based on normal patterns without patient's commands. However, they should be more challenging in cases of subjects with residual motor capacities. This chapter presents the development and definition of diverse control strategies for CPWalker platform. These strategies, both passive and active, will use novel principles of gait rehabilitation to encourage users to participate actively into the therapy. They will look for the best adaptation to the subject's needs for an appropriate recovery.

The elemental control strategies are the base for programming new therapies in CP-Walker. To do that, the chapter describes the frame of a clinician interface through which the physiotherapist can interact with the robot to define a specific therapy. This clinician interface, in conjunction with the control unit and the robotic platform, complete the control architecture of the system.

Finally, selected patient-tailored therapies will be programmed in CPWalker for a first evaluation in three children with spastic diplegia for five weeks. This preliminary clinical evaluation shows the usefulness of CPWalker to serve as a rehabilitation tool.

At the end of the chapter, a control strategy developed for CPWalker is also adapted and applied to LOPES II gait trainer. This implementation shows the potential of the controller and its interaction and applicability to other gait rehabilitation platforms. The *study will be focused on evaluating the algorithm at several amounts of gait speed and PBWS not only for training, but also for a possible assessment tool.*

3.1 Multimodal Human-Robot interface of CPWalker

Brain scans of children with CP (specifically diplegia and hemiplegia) show that the most common finding is damage to Corticospinal Tracts (CSTs) within the Periventricular White Matter (PWM) [127]. These injuries are directly correlated with motor disabilities and voluntary movements performance, since the last are produced through the CSTs [128], see Figure 3.1. To define elemental control strategies of CPWalker, it was required not only a simple rehabilitation of children's gait function, but also the possibility of making discrimination between joints motions and the inclusion of CNS into the human-robot loop. Accordingly, more improvements are expected in the execution of individual movements (both for lower and upper body), and therefore, in the complete gait task.

A MHRI is an interface designed with the aim of integrating the information of both CNS and PNS in order to create a communication bus between the human subject and the robotic device. This technology allows the complete characterization of the patient's state with high details. The MHRIs appeared into the field of rehabilitation with the aim of improving the traditional brain-computer interfaces (BCIs) and brain-machine interfaces (BMIs). These conventional interfaces have been recently used into different contexts, e.g. wheelchairs control [129], reading systems [130, 131], to restore the hand grip function [132], or for the rehabilitation of different motor disorders from

Figure 3.1: Scheme correlation between injury to PWM + CSTs and its interferences with volitional movements in children with CP.

both lower and upper limbs [133–135]. The MHRIs developed in the last years utilized a large number of technologies, which range from very invasive interfaces to measure highly localized groups of neurons [136, 137], to non-invasive interfaces that are based on systems as electroencephalography (EEG) or surface electromyography (EMG) [10].

CPWalker robotic platform has its own MHRI (Figure 3.2), an interface developed to enable the implementation of novel rehabilitation strategies for robot-based therapies. The rationale of the MHRI of CPWalker was to allow integrated PNS and CNS into physical and cognitive interventions, and in a second place, to provide a high versatility to the robotic platform allowing greater adaptability of the therapies to the patient's needs. The combination of the MHRI with therapeutically selected tasks promotes the reorganization of motor planning brain structures and thus, integrating the CNS into the robot-based therapies [138].

In order to develop the MHRI of CPWalker and to select the different technologies that should compose it, three main points were taken into account: i) a previous characterization of the strategies underlying the voluntary movement of children with CP; ii) the neural command from the brain to the muscles (defined as activation patterns [139], and central patterns generators [140]); and iii) the kinematics of measured movements [141]. According to that, the MHRI of CPWalker consists of different sensors (see Figure 3.2): i) an EEG acquisition unit, which is used as a non-invasive way to initiate the therapy basing the decision on patient's intention; ii) inertial measurement units (IMUs) to improve the patients' postural control through active exercises centered on upper body, which are executed in parallel with human-walking patterns; iii) a Laser Range Finder (LRF) to measure free human locomotor patterns and control the robotic platform accordingly; and iv) force sensors located on the structure of the exoskeleton, which are used to implement gait strategies that utilize the patient's collaboration, or to apply adjusted controllers related to intensity and force of each subject. All these emerging sensors gave to clinicians a great possibility of defining specialized and tailored therapies depending on the patient's characteristics, which is a novel concept in the lower-limbs rehabilitation field of children with these types of neurological and motor disorders.

In a nutshell, the MHRI of CPWalker constituted an innovative means to integrate the CNS and PNS into the robotic therapy. First, online characterization of the level of attention (at the CNS) and of the neural drive to muscle (at the PNS) permitted optimizing the therapy in terms of intensity and duration for each user. Second, it enabled the investigation of the motor patterns (at the CNS and PNS) as a method to objectively assess the outcome of the therapy, and also elucidate the neural mechanisms that mediate the recovery. Finally, the adaptation of the therapy by choosing the best sensor-solution for each subject is considered a key feature of CPWalker project. The

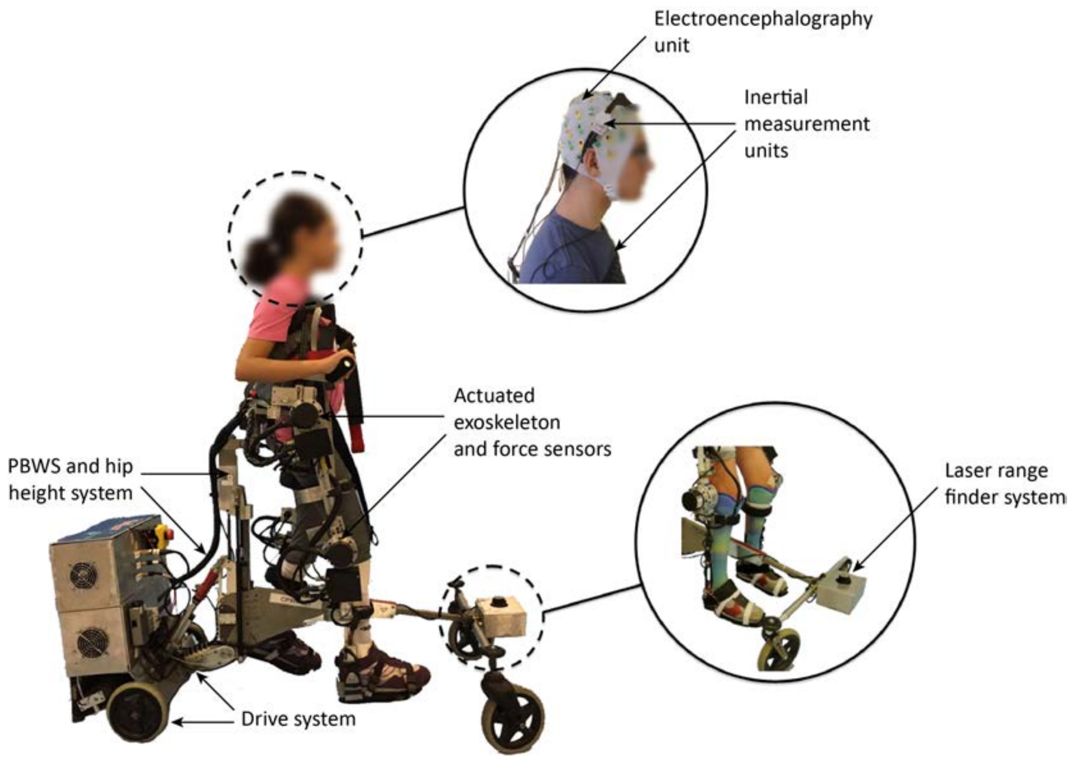


FIGURE 3.2: CPWalker platform and the technology used in the multimodal human-robot interface (MHRI): force sensors, electroencephalography unit, inertial sensors for postural control and laser range finder.

data related to this MHRI is also used to evaluate the results of the therapy regarding the reorganization of neural structures.

The general control scheme that was defined for rehabilitation with CPWalker is shown in Figure 3.3. This conception supported the elemental strategies developed to rehabilitate gait function with the proposed robotic platform. The strategies may be combined, selecting different subtasks of walking for each controller and giving higher versatility to the device. The possibility of selecting the type of control for each joint and for different subtasks of walking is in fact one of the major advantages of CPWalker. It could be associated with better treatment outcomes related with motor control improvements due to the modularity. Moreover, it allows the opportunity of adapting the therapy depending on the user's asymmetry or necessities. One of the goals of making independence between the control of these subtasks is that the patients will be more focused on training specific aspects of walking pattern according to their needs. The hypothesis is that this procedure will help to upgrade results from different measurement scales as the Selective Control Assessment of the Lower Extremity (SCALE) score [128, 142, 143], trying to encourage the children to perform selective voluntary movements. The modular robotic platform, in addition of allowing the individual selection of control strategies, also permits the clinician to enable or disable active joints during training. Greater benefits

FIGURE 3.3: General control scheme developed to implement gait rehabilitation strategies through CPWalker robotic platform.

can be obtained when the patients are focused on defined subtasks than if they have to control all the variables in the first stages of treatment.

Despite all the technologies presented for the MHRI of CPWalker in Figure 3.2, this thesis encompasses the integration of all of them but not their complete development. Concretely, the development of gait guiding strategies and postural control strategies are in the frame of the thesis, being, in contrast, the EEG system [144] and the LRF system [12, 145] studied by other colleagues at gNEC. However all of these systems were part of CPWalker project, and indeed, the author worked to combined all the strategies in CPWalker robotic platform. Subsections below deeply describe the different control strategies developed for CPWalker that were in the frame of this thesis. These strategies had the main goal of making the device adaptable for the implementation of robotic therapies in children with CP.

3.2 Control strategies for robot-based therapies

Gait training in CPWalker is provided according to the level of disability while encouraging patient's participation in the training process. The elemental control strategies of CPWalker were encompassed within a three-tier hierarchical framework that resembles the structure and functionality of the human nervous system (see Figure 3.4). These levels are independent from each other, being able to work together or separately:

- **Low-level:** At the low-level, diverse gait guiding strategies are used to calculate the error between the current and desired position of the device. These strategies are individually defined for each actuated joint and different levels of assistance depending on the user's capabilities. At this level, the actuation of the device is predominant over patient's operation.

- **Mid-level:** At the mid-level, a multi-joint adaptive controller is the responsible of autonomously switching between the different locomotive strategies of the low-level. The decision of the adaptive controller is based on user's performance during the exercise, and can vary in real-time fitting the robotic assistance for various subtasks of walking within the gait cycle.

- **High-level:** At the high-level, several control strategies perceive user's intent related to different locomotive aspects. In this regard, user's intention is predominant over robot state, and it is mainly represented by three technologies of the MHRI of CPWalker: EEG unit for triggering the begin of the gait [144], LRF for commanding the walking speed through free human locomotor patterns [12, 145], and IMUs for active postural control of head and trunk. As was previously indicated, of these three strategies, the two first are out of the framework of this thesis, so only the last one is covered in details by the sections below.

Following subsections explain in detail the technological and theoretical approaches implemented to fulfil the three levels previously described. At the end of each point, author gives a technical evaluation of the essential parts presented. They are not clinical validations, instead they were designed to demonstrate that the different components were integrated into the control strategies and crucial systems were correctly performed. These technical evaluations had the main goal of enabling the author and clinical staff to design a robot-based protocol for a future use of CPWalker platform as benchmark for

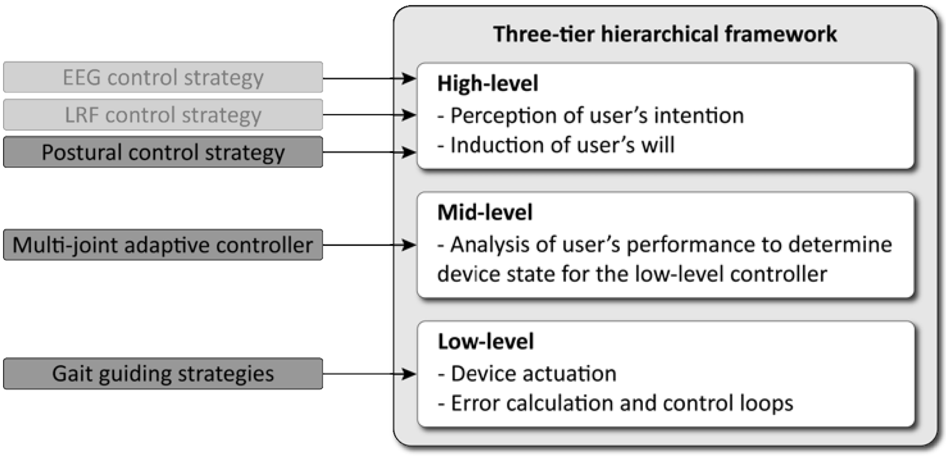


Figure 3.4: Hierarchical framework for elemental control strategies of CPWalker platform. At the high level, only the postural control strategy is within the framework of this thesis.

the experimentation with real pediatric patients. The possibilities offered by CPWalker were the base of this future novel protocol, which will be exposed in the next chapter.

Technical evaluations were tested in both, healthy users and in some cases, in children with CP. The tests with children were under the supervision of the clinical staff at HNJ. For these cases, the local ethical committee of HNJ gave approval to the technical experiment and warranted its accordance with the Declaration of Helsinki. All patients were informed beforehand and signed through parents a written informed consent to participate.

3.2.1 Low-level: gait guiding strategies

The control of gait guiding strategies for lower-limbs exoskeletons is an essential part of desired robot-based therapies. Fixing prescribed gait patterns is important in order to teach proper movements to the patients. With them, robot-aided gait training reduces physical load on the therapists at the same time that the number of sessions and the precision of the exercises are increased. However, once patients perform a phase with enforcing gait to fixed trajectories in space and time, next step should be to encourage them to a more active participation. Therapies may be tailored depending on the phase of rehabilitation and the patient, increasing patient's collaboration to optimize the efficiency of robotic rehabilitation.

This section describes the control algorithms developed in CPWalker to implement gait strategies that served as the base for future exercises with the exoskeleton. First rehabilitation phases will be covered by strategies that will guide lower limbs following predefined and fixed gait patterns. Nevertheless, AAN strategies will be part of more advanced trainings that will require patients' movement collaboration. Training with adaptive gait patterns through impedance controllers has the main advantage of giving more physiological and variable sensory input to CNS, and it also increases the patient's motivation. Force sensors are indispensable elements to put into effect these novel strategies as impedance control, or force resistor control besides trajectory tracking. Moreover, force sensors also provide measurements in order to prevent undesired efforts of the robot on child's body.

In CPWalker, different control modes individualized per joint distinguish several robotic assistance levels in between two extremes: "robot in charge" and "patient in charge" (Figure 3.5). Three levels of impedance were taken into account in addition to position control (P) and force control (F): high impedance (HI, more proximal to "robot in charge" mode), medium impedance (MI) and low impedance (LI) controllers, respectively. These controllers may be individually established per joint, defining the patients'

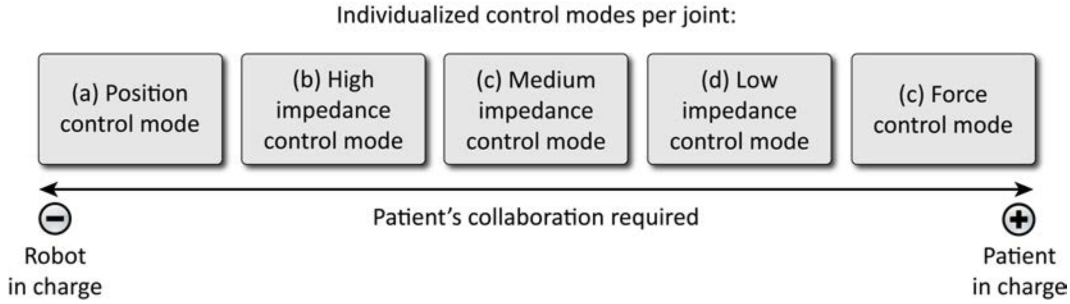


FIGURE 3.5: Scheme of controllers according to "robot in charge" or "patient in charge" levels. From less to more patient's collaboration the control modes are: (a) position control mode, P; (b) high impedance control mode, HI; (c) medium impedance control mode, MI; (d) low impedance control mode, LI; and (e) force control mode, F.

collaboration according to their capacities. This possibility made CPWalker a modular robotic platform. Subsections below describe the individualized controllers and a brief technical validation of them.

3.2.1.1 Position control strategy

Trajectory tracking or position control is a strategy based on the principle of guiding the user's limbs on fixed reference gait trajectories, [121, 146, 147]. This method was one of the first implemented in the rehabilitation robots and has been proven to be effective for severely affected patients [61, 148–150].

Trajectory control strategy consists on an internal control loop which uses the error angle (θ_{error}) provided by the difference between a reference of prescribed gait pattern (θ_{ref}) and the angle measured on each exoskeleton joint (θ), (see Figure 3.6). For its control, reference trajectories are required, which normally consist of normal gait patterns represented by joint angles that are highly dependent on walking speed [151].

An important question for gait rehabilitation devices is how to assist the patient with the minimum interaction forces between robot and human. This implies that subjects will be able to walk more naturally maintaining the safety, stability and effectiveness of the system. In order to achieve this, the gait pattern applied by the robotic device

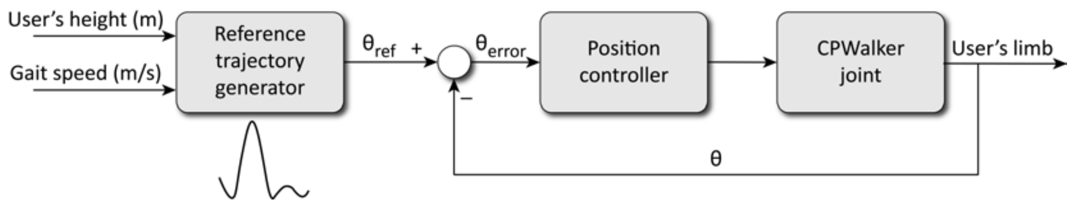


FIGURE 3.6: Position control algorithm. The error of each joint (θ_{error}) passes through a *position controller* box, which is a proportional controller whose parameters are individually selected for each joint of the exoskeleton.

must be adapted both to the individual user and to the characteristics of the gait. The reference trajectories of CPWalker platform were generated according to the algorithm presented by Koopman et al. in [151], which reconstructs reference joints trajectories based on user's height and gait speed. These reference trajectories are given by joint angles (θ_{ref}) in a complete gait cycle. The controller of each joint was responsible of ensuring the guidance of its own motion in order to get a correct normal gait pattern in the whole exoskeleton.

The reference trajectory corresponded to a matrix of three columns (hip, knee and ankle) and 200 rows (angles of the ROM required in sagittal plane along the gait cycle) (3.1), which came from the spline-interpolation of the result obtained with the regression models of [151]. The number 200 was chosen with the goal of getting a gait pattern signal with enough sampling rate, such that it does not lose accuracy with the minimum number of points.

$$\theta_{error} = \theta_{ref} - \theta = \begin{pmatrix} \theta_{refHip} \\ \theta_{refKnee} \\ \theta_{refAnkle} \end{pmatrix}^T - \begin{pmatrix} \theta_{Hip} \\ \theta_{Knee} \\ \theta_{Ankle} \end{pmatrix}^T = \begin{pmatrix} \theta_{errorHip} \\ \theta_{errorKnee} \\ \theta_{errorAnkle} \end{pmatrix}^T \tag{3.1}$$

One of the main parameters that may be selected by the clinician and that has direct effect on the generated gait pattern is the total percentage of ROM applied. In that way, the amplitude of the calculated trajectory will be reduced as much as this percentage indicates. On the other hand, if the gait speed is modified, the number of rows in the gait pattern will be the same, but it will change the time of permanence in each sample, and consequently, the sample frequency. Figure 3.7 illustrates an example of these changes, where four reference trajectories for a person of 1.7 m of total height, are represented respect to percent of gait cycle: i) Trajectory 1 (continuous yellow line in Figure 3.7) corresponds to a gait speed of 0.55 m/s and ROM of 100%; ii) Trajectory 2 (dotted yellow line in Figure 3.7) corresponds to a gait speed of 0.55 m/s and ROM of 70%; iii) Trajectory 3 (continuous blue line in Figure 3.7) corresponds to a gait speed of 0.28 m/s and ROM of 100%; and iv) Trajectory 4 (dotted blue line) corresponds to a gait speed of 0.28 m/s and ROM of 70%. Note that ankle reference trajectory was also implemented in the calculation algorithm in case that CPWalker incorporates active ankles in the future.

With this simple strategy, the exoskeleton was able to guide patient's lower limbs following reconstructed normal trajectories for any given speed.

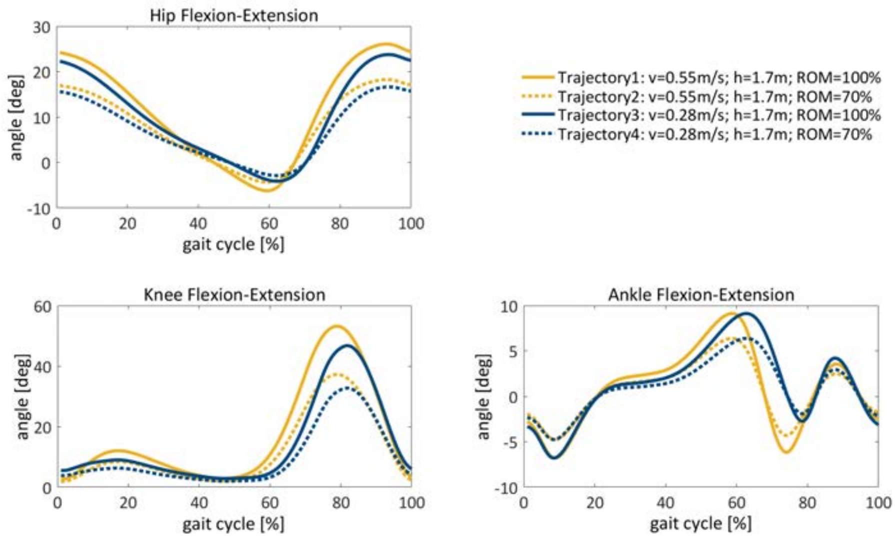


FIGURE 3.7: Changes in reference trajectories (θ_{ref}) for hip, knee and ankle flexion-extension depending on different parameters as percentage of ROM applied and gait speed.

3.2.1.2 Selective impedance control strategy

Although position control has been proven with positive results in several cases [61, 148–150], robot-based therapies might be optimized in order to increase the patient's participation, because with a pure training of trajectory tracking, users might tend to walk passively. Moreover, user's contribution is an important aspect to develop neuroplaticity and motor control [7, 8, 146]. The active participation may be achieved both by incrementing the user's motivation or by requiring self activity [85]. The latter can be implemented through AAN algorithms and impedance methods.

The impedance control was introduced by Hogan in 1985 in three parts [152]. In his work, Hogan presented an approach to the control of dynamic interaction between a manipulator and its environment. In the study, the concept of "mechanical impedance" was applied to search an approximation for robotic control. The impedance of a system (Z(s)) is defined as the relation between the force of this system (F(s)) against an external movement imposed upon it and the movement itself ($\theta(s)$) [152]. This relation between interaction forces and position angles is known as "mechanical impedance", and in biomechanics it is often defined as the dynamic behaviour between joint torque and angular displacement [153]. In general, the impedance involves three components: stiffness, damping and inertia. The equation that relates force and position is shown below:

$$Z(s) = \frac{F(s)}{\theta(s)} = I \cdot s^2 + B \cdot s + K \tag{3.2}$$

that means:

$$F(t) = I \cdot \ddot{\theta} + B \cdot \dot{\theta} + K \cdot \theta \tag{3.3}$$

In Equations 3.2 and 3.3, the zero order term (K) is called stiffness and describes the relation between the force exerted by the actuator and its position; the first order term (B) is the damping and represents the relation between force and velocity; and the second order term (I) is named inertia and describes the relation between force and acceleration of the system. θ, $\dot{\theta}$ and $\ddot{\theta}$ are position, velocity and acceleration of the device respectively.

Following the impedance concept developed by Jezernik [146], and Riener et al. [111], for the Lokomat robotic trainee, a new impedance algorithm was implemented in CPWalker, which attempted to prevent undesired efforts on patients' lower limbs and, most important, to apply the philosophy of AAN to take advantage of patients' residual movement. The method considered the human-exoskeleton interaction to allow a variable deviation from the predefined reference trajectory, [111, 121, 146, 147]. The approach proposed (Figure 3.8) was based on a cascaded *position and force controllers*, whose internal loop was able to track force profiles in a determined bandwidth. In case of CPWalker, real rotation angles (θ in Figure 3.8) were provided by the potentiometers located in each joint of the exoskeleton and torques (τ in Figure 3.8) were measured by the force sensors coupled to the structure.

In order to perform parameters identification for both *position and torque controllers*, author took into account that CPWalker moves with sufficiently low values of velocity and acceleration and, consequently, the effects of inertia and damping could be disregarded. Besides, the adjustment followed empiric trial and error calibrations without human users. The *torque controller* was adapted in first place, keeping the proportional *position controller* equals to zero. Once a proper torque tracking with a zero set point was ensured, the external position loop started to be adjusted, which tries to perform

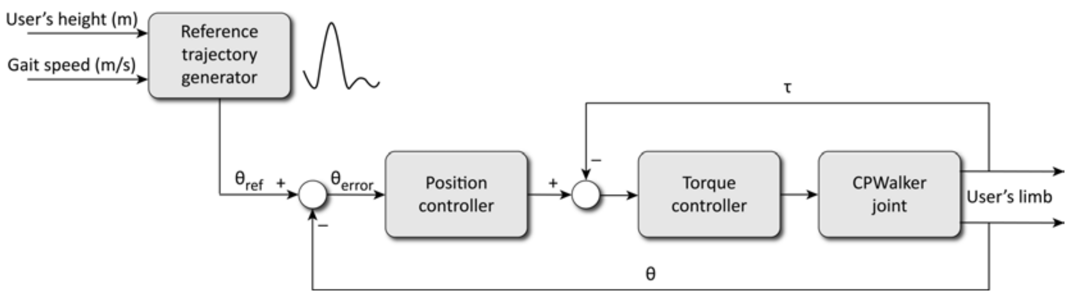


FIGURE 3.8: Impedance control algorithm. Two loops compose the impedance algorithm, treating the error generated through two controllers: *position controller* box and *torque controller* box. The parameters of each controller are individually selected for each joint.

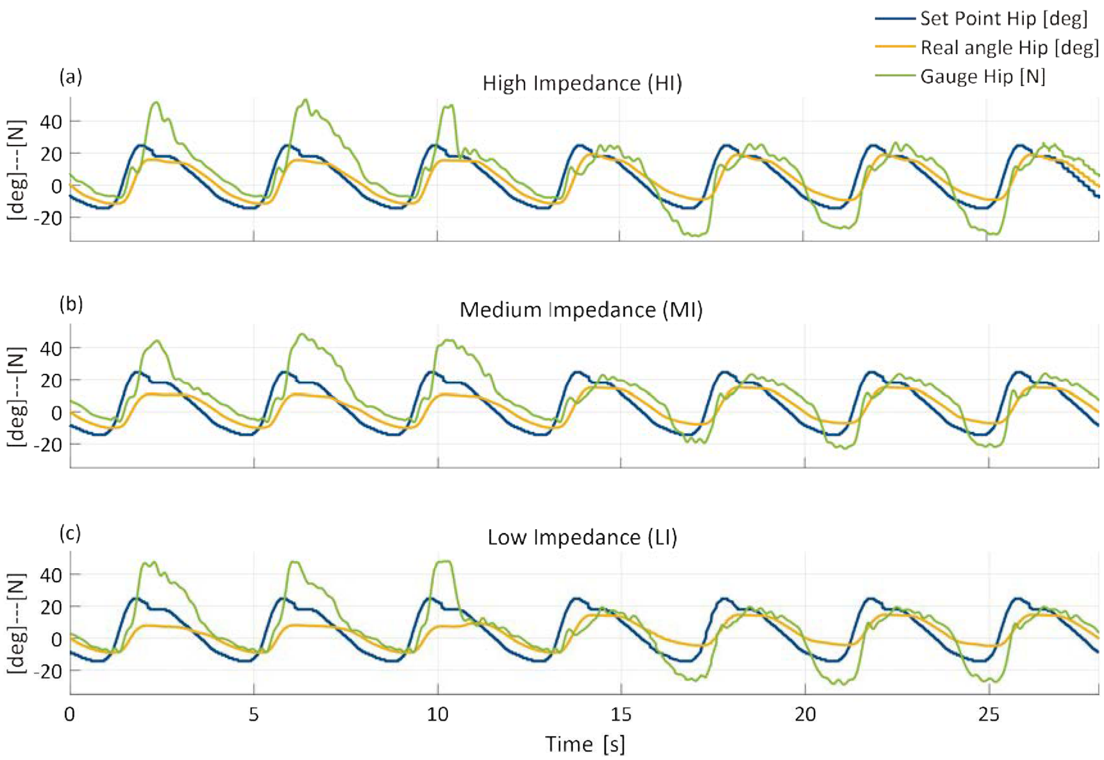


FIGURE 3.9: Different levels of impedance control strategy depending on the assistance provided: (a) high impedance, (b) medium impedance and (c) low impedance. Similar values of references (blue lines) and forces (green lines) cause diverse real trajectories (yellow lines) according to the type of impedance level.

the generated trajectories in joint-space if the force detected by the strain gauges of the exoskeleton is close to zero. The relation between both loops determines the impedance applied by the exoskeleton to user's lower limb movements.

Following this approach, the impedance control algorithm of CPWalker was set to provide three levels of AAN (see Figure 3.5): i) high impedance (HI); ii) medium impedance (MI); and iii) low impedance (LI). The relations between the extremes of impedance modes (HI and LI modes) respect to the MI were determined increasing and decreasing around 50% the impedance parameters. Consequently, if the position controller is higher, the torque controller must be reduced and vice versa. Figure 3.9 represents the effects of each level of impedance in hip joint for the same values of reference trajectory (blue line) when similar force values (green line) were intentionally applied in opposition of movement. With a high level of impedance established (Figure 3.9 (a)), the real trajectory of the exoskeleton (yellow line) followed in a better way the imposed reference (blue line). This situation is closer to trajectory tracking control. The opposite situation occurred with a low level of impedance (Figure 3.9 (c)), since in this case, the user is who has more participation in the control of CPWalker, without becoming a total management of the device.

Each joint of the exoskeleton has its own impedance controller with specific parameters estimated individually for each case and control mode, so the assistance may be generated separately for each part of the exoskeleton. That means that the type of control may be selected separately for each joint, but the tracking is ensured in all the exoskeleton because the reference is sent for all the controllers in each cycle. As it was previously indicated, this possibility increased the modularity of the system.

3.2.1.3 Force control strategy

The last strategy related to gait guiding is a force-based walking controller developed with two aims: i) to give the complete control to the user ("patient in charge" mode); and ii) to allow strength training exercises with CPWalker in order to increase the benefits of the treatment and to contribute with a high versatility of the device. This strategy, which was based on the algorithm exposed by Figure 3.10, was intended for the final stage of a robot-based training program, when the patient has already learned the correct movements of lower limbs for a proper normal walking through other control strategies as trajectory tracking or impedance modes.

In the case of force strategy, a reference pattern is not necessary, because the user is now encouraged to handle the motion. In the diagram of Figure 3.10, an absolute value of set point force is selected by the clinician (F_{ref}), and it is compared with the real forces (F) measured through the strain gauges of the joints. The box *error adjustment algorithm* in Figure 3.10 has the purpose of classifying the force error (F_{error}) depending on which movement is being performed: flexion or extension. Concretely, the classification is done following the Equation 3.4:

$$F_{error} \begin{cases} F_{ref} - F, & |F| > F_{ref} \ and \ F > 0 \\ -F_{ref} - F, & |F| > F_{ref} \ and \ F < 0 \\ 0, & |F| \leq F_{ref} \end{cases} \tag{3.4}$$

The classified error passes through a *force controller* that fits the control signal for the individual joints of the exoskeleton with the goal of getting a $F_{error} = 0$.

The value of F_{ref} selected by the clinician was understood as a force that needs to be overcome by the patient in order to produce a movement. This type of exercises are expected to enhance the user's active participation, training in that way the strength capabilities. A concrete and interesting mode of this strategy is the zero-force control ($F_{ref} = 0$), where the patient may move the lower limbs with free motion and minimum interaction with the exoskeleton. When zero-force control is applied, the smart walker

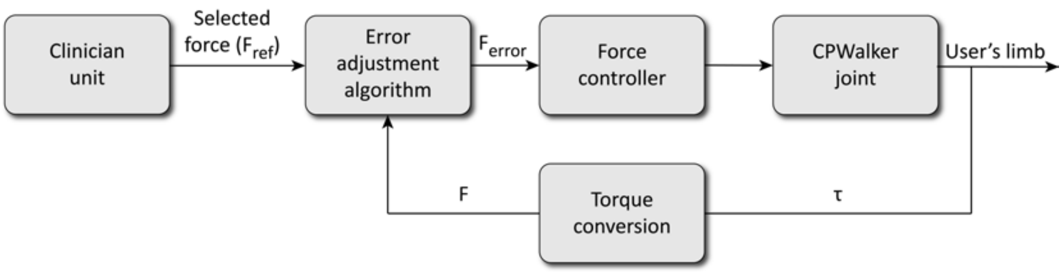


FIGURE 3.10: Force control algorithm. The measured force for each joint of the exoskeleton is compared to a force to overcome selected by the clinician. The error is adjusted depending of movement (flexion or extension), and subsequently, it passes through a *force controller* box whose parameters are individual for each joint.

calculates the speed for the displacement through the LRF sensor. The algorithm of the LRF sensor scans the location of the patient's lower limbs and measures the cadence and step length to calculate de velocity for the drive system. More details related to the LRF algorithm may be consulted in [12, 145].

3.2.1.4 Technical evaluation of gait guiding strategies

The fact of obtaining positive results from the technical validation of gait guiding strategies is a fundamental point to prove that CPWalker could serve as a novel rehabilitation tool. The control strategies as trajectory tracking and selective impedance were previously tested in healthy subjects before to perform a studied clinical evaluation. After these experiments with healthy users, author evaluated if the behaviour of the system was maintained with two children with CP. As an example of the obtained outcomes, Figure 3.11 represents graphics of 100 s capture data from the technical validation with one of the pediatric patients (GMFCS IV) at the HNJ. In this case, the training consisted on walking with CPWalker with position control (P) applied on the knee joints and high impedance control (HI) imposed on the hips, in order to test both control strategies at the same time. In Figure 3.11 (a) and (b) it is possible to see that the delay between "real movement" (yellow) and "set point" (blue) for both knees is almost non-existent, which means that the prescribed walking pattern is imposed upon the subject, and the legs were moved following this prescribed pattern. However, in graphics that correspond to hips (Figure 3.11 (c) and (d)), it is possible to appreciate that the "real movement" in yellow lines differs from "set point" (blue lines) according to the measures of the strain gauges or force sensors (green lines). There is here the evidence that the human-robot interaction is presented through the impedance control strategy, and with it, the patient was encouraged to actively participate in the exercise. Concretely, for this user, the biggest challenge was the extension movement on the hip joints, as can be verified in

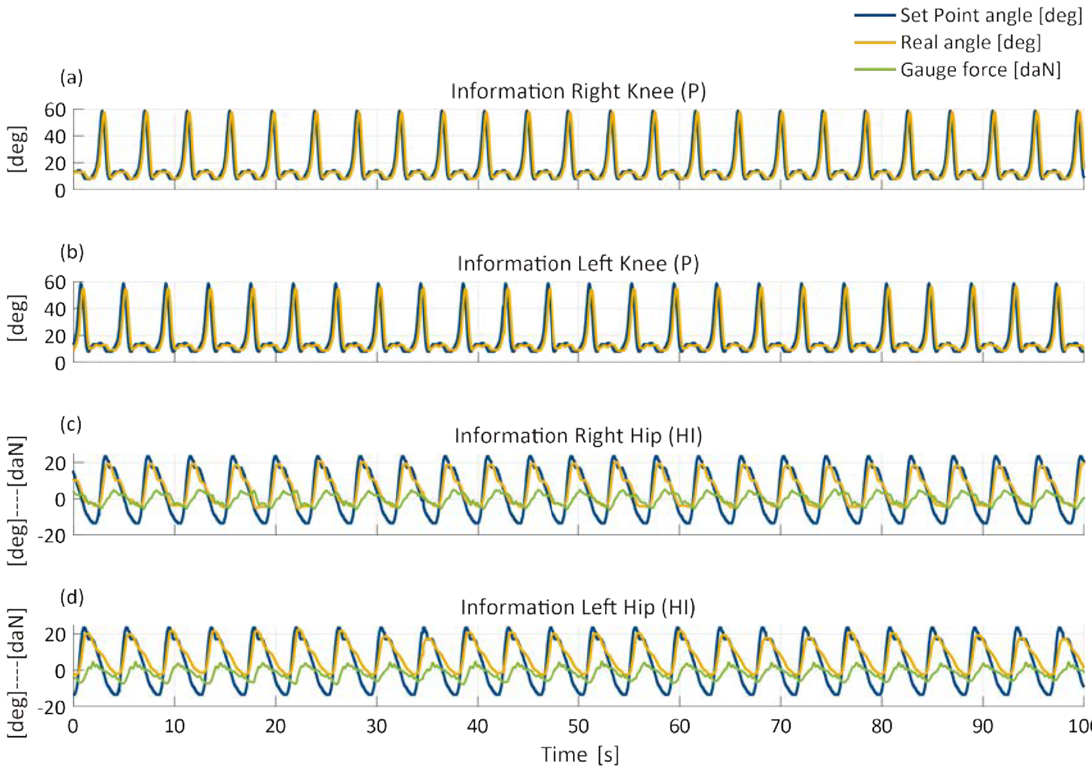


FIGURE 3.11: 100 s capture data from a technical validation with a patient with CP (GMFCS level IV), using position control (P) on the knees and high impedance control (HI) on the hips. Blue lines represent the reference trajectories provided by the mathematical models implemented in CPWalker; yellow lines are the real movements described by the user's lower limbs; finally, green lines denote the measures of the strain gauges in case of impedance control.

Figure 3.11 (maximal hip extension movement is where "real" and "set point" differ the most).

As another example, Figure 3.12 represents an interval of 60 s recorded with a second patient with CP (GMFCS II). In this case, the child walked with CPWalker following medium impedance for all the joints. The colour code is the same than the previous figure, but in this case the data for knee-gauges is also represented (green lines in Figure 3.12 (a) and (b)). The controller actuated under the same approach for knees and hips, save that during the stance phase of gait, data from knee-gauges was not taken into account, leaving the knees to follow the impedance mode only during the swing period.

The presented strategies, working in parallel with others technologies as EEG or tactics as the improvement of postural control, offer the contribution of supraspinal structures in the control of walking, which is a key factor for the recovery of patients with this type of disorders.

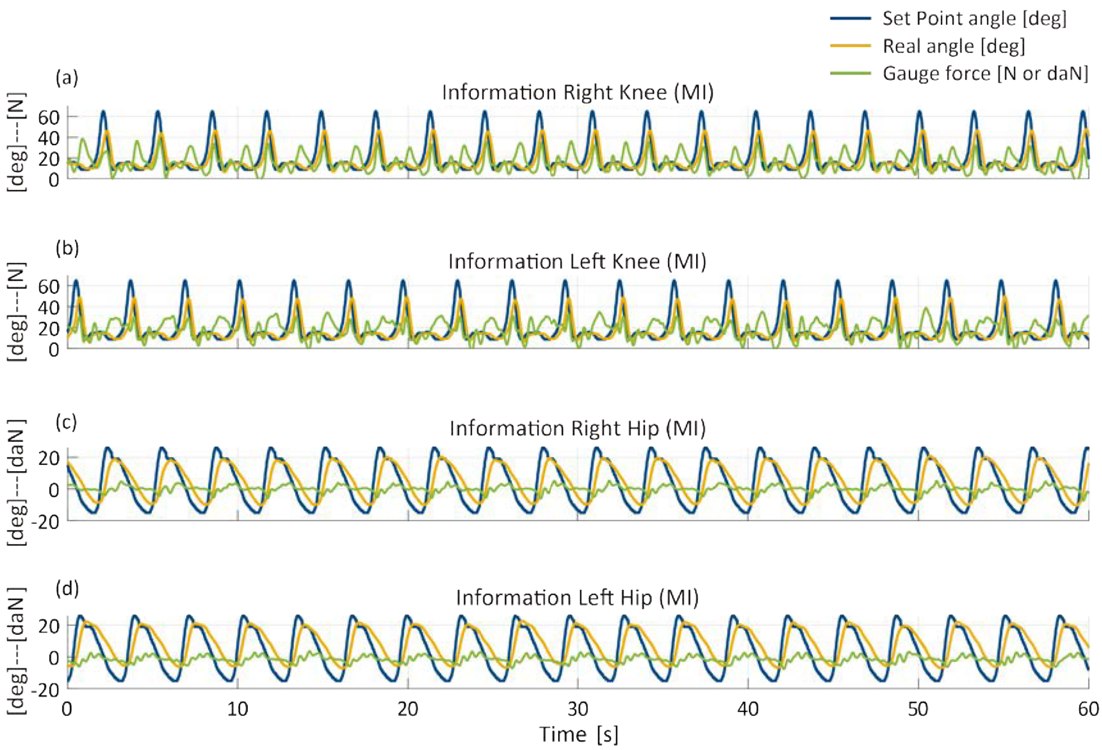


FIGURE 3.12: 60 s capture data from a technical validation with a second patient with CP (GMFCS II), following medium impedance (MI) for all the joints of the exoskeleton. Blue lines represent the reference trajectories provided by the mathematical models implemented in CPWalker; yellow lines are the real movements described by the user's lower limbs; finally, green lines denote the measures of the strain gauges in case of impedance control. Impedance mode for knee joints is only available during swing phase of gait.

3.2.2 Mid-level: multi-joint performance-based adaptive algorithm

One of the main limitations to implement robotic rehabilitation in children is the therapy design. There is not an optimal treatment that covers all the requirements independently of the user. Previous subsections have exposed different gait guiding strategies, which could be implemented in the exoskeleton of CPWalker or another lower-limb exoskeleton prepared for that. Although the possibility of adjusting diverse assistance individually per joint gives a high versatility for the treatment design, so far must be the therapist who manually chooses the parameters for the therapy. The future technical challenges should encourage the patients, introducing not only specific and repetitive movements with a high intensity, but also innovative strategies that help to improve the effectiveness of the therapy through objective decisions. Physiotherapists or practitioners need some tools to objectively decide the best treatment option for each patient, specially if they can select from too many options as CPWalker offers for each joint. Thereby, the customization of the exercise to the patient's progression will be as good as desirable.

Throughout this thesis, author has demonstrated important advantages of developing tailored therapies to address different patients' needs and capabilities, some of them collected in the bibliography [13, 154, 155]. Task-specific and active participation are crucial factors for motor learning. The grade of assistance through different levels of impedance as those exposed previously, is important to enhance the voluntary participation and thereby, the patients' motor plasticity [156, 157]. Decreasing the assistance during learning new exercises encourages the user to generate muscle force to fulfil the task. Some of the current robotic devices (not only for CP, but also other neurological diseases) have incorporated novel AAN strategies to stimulate the user's contribution: e.g. MIT-MANUS [154] for upper limbs or Lokomat [158] and LOPES II [91] for lower limbs. In general, the AAN strategies, which are normally based on impedance controllers, could be divided in two groups: i) *basic impedance*, which assists the user as needed in order to ensure a correct position tracking despite the high or low patient's collaboration; and ii) *robust impedance*, which helps the patient when motion begins but limits the assistance while the user completes a pre-defined task, whose challenge could vary depending on the user's performance. So far, both basic and robust controllers have the same disadvantage that the therapy could be affected by subjective decisions.

To address the presented issues, a novel and robust multi-joint adaptive impedance behaviour was implemented in CPWalker looking for more flexible and tailored therapies for pediatric population. The model (represented in Figure 3.13) is capable of autonomously adapting the robotic assistance within the exercise based on patient's performance. The controller evaluates patients' performance (θ) with respect to the reference trajectory (θ_{ref}) in a defined number of preceding steps ($T_{evaluation}$). The evaluation is carried out looking at specific key points into the gait cycle (concretely maximal flexion and extension values for hip and knee joints). Based on this evaluation, the adaptive controller calculates the new control mode of assistance for each joint (χ_{new}). The parameters that are needed to be selected only once and before to start the therapy are: i) the gait velocity; ii) the percentage of ROM; iii) the default control mode for each joint ($\chi_{default}$); iv) the challenge of the task ($\%\Psi$); and v) the evaluation time ($T_{evaluation}$) of the performance.

The adaptive impedance controller starts with a default control mode of assistance per joint ($\chi_{default}$), and progresses toward more difficult control modes (more patient's participation) as the patient performs the required movement together with the proposed challenge ($\%\Psi$). The decision of changing the control mode autonomously is made in the *Performance-based adaptive controller* box of Figure 3.13. If the challenge is not achieved in the $T_{evaluation}$, the control mode returns to an easier level (i.e. the robot provides more assistance). In summary, the adaptive controller may adjust the robotic assistance individually per joint in three ways:

- By adapting the mechanical support of each joint to the five possible control modes of CPWalker (*Control mode implementation* box in Figure 3.13; i.e. χ_{new} may take any value of the five control modes: P, HI, MI, LI or F). Control modes with lower impedance (more difficult levels) require more patient's collaboration to achieve the desired gait pattern (θ_{ref}). In that case, the width of the tunnel permitted around the θ_{ref} becomes bigger as the level is more difficult, resulting in a increased possibility of making movement errors (patient's performance θ remote from the desired pattern θ_{ref}).

- By modifying the challenge of the task ($\%\Psi$ in Figure 3.13). The challenge is referred to the percentage of the θ_{ref} that is required to be achieved by the patient. For the calculation (*Performance-based adaptive controller* box in Figure 3.13), author took into account the differences between the patient's performance (θ) and the requested pattern (θ_{ref}) at the maximum values of flexion and extension of each joint in each step. The percentage per joint is calculated as the average of both values (flexion an extension), assuming that if these peak values are achieved in amplitude and time, the rest of gait pattern is well performed since they are the most critical points and the gait pattern is repeated periodically in rehabilitation exercises.

- By adjusting the evaluation time ($T_{evaluation}$ in Figure 3.13) considered as number of previous steps to evaluate the performance before to update the new control mode (χ_{new}) that will be implemented in the joint. Therefore, the χ_{new} is actualized after groups of n steps ($T_{evaluation}$ = n).

Summary:

- Position (P), High impedance (HI), Medium impedance (MI), Low impedance (LI), Force (F).
- Desired gait pattern (θ_{ref}), patient's pattern performance (θ).
- Control mode of assistance χ, which could be default ($\chi_{default}$) or new (χ_{new}). It can take any value of the possible modes (P, HI, MI, LI, F).
- Challenge $\%\Psi$, which is a threshold that indicates the percentage of θ_{ref} to achieve.
- Evaluation time of performance $T_{evaluation}$, measured in number of steps.

In order to succeed the previous points, the percentages of performance for hips and knees (flexion = maximum value; extension = minimum value), were decided to be

Figure 3.13: Adaptive impedance controller of CPWalker. Brown square is the calculation block, where the user's performance is analysed based on the achievement of $\%\Psi$ in $T_{evaluation}$. When χ_{new} is determined, it needs to be chosen from the five control modes of CPWalker (blue square). The control signal produced by the control mode is sent to CPWalker joint (green square) in order to produce the movement.

normalized and calculated as Equations 3.5, 3.6 and 3.7 indicate. These equations "penalize" users' performance applying more robotic assistance in case that they do not reach the desired reference, but not if they overcome it. Concretely, the hip flexion-performance was determined similarly to the knee formulation, taking the appropriate parameters for each joint (Equation 3.5), where $T_{evaluation}$ = n.

$$\%Flex_{Hip} = \%Flex_{Knee} = \frac{\frac{\sum_{i=1}^{n}(\theta^{max})_i}{n}}{\frac{\sum_{i=1}^{n}(\theta_{ref}^{max})_i}{n}} \cdot 100 = \frac{\sum_{i=1}^{n}(\theta^{max})_i}{\sum_{i=1}^{n}(\theta_{ref}^{max})_i} \cdot 100 \tag{3.5}$$

Nevertheless, for the extension-performance different calculations are necessary (Equations 3.6 and 3.7) due to the hip extension achieves negative values but the motion for knee joint is always positive in CPWalker.

$$\%Ext_{Hip} = \frac{\frac{\sum_{i=1}^{n}(\theta^{min})_i}{n}}{\frac{\sum_{i=1}^{n}(\theta_{ref}^{min})_i}{n}} \cdot 100 = \frac{\sum_{i=1}^{n}(\theta^{min})_i}{\sum_{i=1}^{n}(\theta_{ref}^{min})_i} \cdot 100 \tag{3.6}$$

$$\%Ext_{Knee} = \frac{2 \cdot \dfrac{\sum_{i=1}^{n}(\theta_{ref}^{min})_i}{n} - \dfrac{\sum_{i=1}^{n}(\theta^{min})_i}{n}}{\dfrac{\sum_{i=1}^{n}(\theta_{ref}^{min})_i}{n}} \cdot 100 = \tag{3.7}$$

$$= \frac{2 \cdot \sum_{i=1}^{n}(\theta_{ref}^{min})_i - \sum_{i=1}^{n}(\theta^{min})_i}{\sum_{i=1}^{n}(\theta_{ref}^{min})_i} \cdot 100$$

The total percentage for each joint is determined averaging the results obtained for flexion and extension of the respective joint in the group of "n" steps (Equation 3.8):

$$\%Total_{joint} = \frac{\%Flex_{joint} + \%Ext_{joint}}{2} \tag{3.8}$$

Once the total percentages of performance are obtained, the new control modes (χ_{new}) are actualized individually following the criteria exposed before, where two situations may be found (Equation 3.9): i) if the total percentage is lower than the selected threshold or challenge ($\%\Psi$), this means that the patient did not achieve the goal in $T_{evaluation}$, so χ_{new} will decrease to an easier level (higher impedance, $\uparrow k$, which implies more assistance); ii) if the total percentage is equal or bigger than $\%\Psi$, the difficulty of the level may be increased (lower impedance, $\downarrow k$, which implies less assistance).

$$\begin{cases} \%Total_{joint} < \%\Psi & \Rightarrow \downarrow \chi_{new}^{joint} \Rightarrow \uparrow k^{joint} \\ \%Total_{joint} \geq \%\Psi & \Rightarrow \uparrow \chi_{new}^{joint} \Rightarrow \downarrow k^{joint} \end{cases} \tag{3.9}$$

The controller proposed here is multi-joint adaptive, which means that each joint may be adjusted independently into the same exercise. The major advantage of using this controller is not only assist the patients as needed, but also encourage the users to reach the motion goals by changing the challenge according to their performance. The active promotion of user's participation through voluntary motion is expected to contribute with larger functional gains. Furthermore, as the user's performance is evaluated in real-time, the patients' motivation could be increased, avoiding discouraging them by the adaptation of the challenge task in order to promote the success rate. Finally, the design of the therapy should improve because it is not affected by subjective decisions from physiotherapist's human behaviour.

3.2.2.1 Technical evaluation of performance-based adaptive algorithm

The proposed algorithm was in a first place modeled in Simulink in order to test a brief simulation of its functioning for each joint, and subsequently, it was technically evaluated with a female healthy user of 58 kg of weight. The exercise with the healthy user was implemented through a flat and straight surface, and it consisted of two phases: i) a first phase to get accustomed to the device, in which the user walked with the robot around 30 m following a permanent position mode in all the joints; ii) a second phase where the adaptive impedance controller was evaluated in the exoskeleton of CPWalker for a similar distance of 30 m. In this phase, the user walked with the multi-joint adaptive controller activated in the exoskeleton, starting with $\chi_{default} = P$ for all the joints, and progressing according to her performance. The selected constant parameters for the adaptive controller where: $\%\Psi = 85\%$ and $T_{evaluation} = 3\ steps$. Both phases were carried out with ROM = 100% of the maximum gait pattern of CPWalker, PBWS = 20% of the total user's weight, and velocity = 30% of the total provided by CPWalker (100% correspond to 0.6 m/s).

Figure 3.14 represents an interval of 70 s selected from the total path performed by the healthy user with the adaptive controller activated. The shown data correspond to the movement of right hip during this interval. Concretely, Figure 3.14 (a) is the comparison of the percentage of user's right hip evaluated each 3 steps (pink line), respect to the desired percentage ($\Psi = 85\%$, represented in blue line). Figure 3.14 (b) represents the blocks of three steps (blue line), and the change of the control mode for right hip (χ_{new}, pink line) according to the percentages achieved in Figure 3.14 (a): if the achieved percentage is bigger than $\%\Psi$, χ_{new} goes towards a more difficult control mode, and the opposite. Finally, Figure 3.14 (c) is the representation of the user's performance on right hip for each step (blue line is the reference of the set point θ_{ref}, and yellow line is the real movement of the user θ). As may be observed, cases in which user's performance decreased were mainly caused because of the fact that maximal hip extension was not enough. The performance data for the rest of joints in the same period of time is collected in Table 3.1, where bold values mean that $\%\Psi$ was overcome by the user, and (*) is referred to values higher than 100% because the user's flexion-extension set was bigger than that given by the set point.

3.2.3 High-level: biofeedback strategy for postural control

Children with CP present an altered gait pattern with an increased ROM of the trunk during gait. Usually, they walk looking at the ground, with their head down. Some references in the bibliography ensure that to maintain a proper posture during walking

FIGURE 3.14: Right hip interval of 70s selected from the user's performance with CPWalker using the multi-joint adaptive impedance controller. (a) represents the comparison between the percentage achieved by the user each 3 steps (pink line) respect to the desired challenge $\%\Psi$ (blue line). (b) shows the change of χ_{new} (pink line) each 3 steps (blue line) depending on the percentage in (a). (c) is the graph of the user's performance: yellow line is the real motion and blue line is the set point.

TABLE 3.1: Data for all the joints during the period of 70 s selected from the exercise with the healthy user. G0 to G6 are the groups of 3 steps implemented during this period. The table gives the progression of χ_{new} depending on the $\%\Psi_{achieved}$ in the last group of steps. Bold values represent $\%\Psi_{achieved} > \%\Psi$, and (*) means $\%\Psi_{achieved}$ $> 100\%$ because the user's flexion-extension set was bigger than that given by the set point.

		G0	G1	G2	G3	G4	G5	G6
Right hip	χ_{new}	P	HI	P	HI	MI	HI	MI
	$\Psi_{achieved}$	95.43	82.05	**92.18**	**86.14**	79.08	**86.29**	76.38
Left hip	χ_{new}	MI	HI	P	HI	P	HI	P
	$\Psi_{achieved}$	78.64	77.11	**91.17**	82.19	**97.09**	84.59	**95.67**
Right knee	χ_{new}	P	HI	MI	LI	LI	LI	LI
	$\Psi_{achieved}$	**113***	**100.6***	**95.89**	**100.9***	**95.27**	**102.7***	**93.11**
Left knee	χ_{new}	P	HI	MI	LI	LI	LI	LI
	$\Psi_{achieved}$	**95**	**96.67**	**97.13**	**96.50**	**97.19**	**95.77**	**90.87**

is a relevant aspect, specially in the case of children with CP [88, 96, 97, 159]. These problems must be attended as independent movements limitations, and rehabilitation strategies must be oriented to correct them [160].

To address these issues, author developed an active postural control strategy based on CPWalker, which is intended to be used while over-ground movement in real environment is allowed. The rationale of this control strategy was to enhance the cognitive interaction between the child and the robot, improving the postural control through that.

IMUs sensors (TechMCS, Technaid, Spain) were used as the main part of a biofeedback strategy developed to improve the children's postural control during robot-based gait therapies. Two IMU sensors, placed on the user's chest and head, measure in real-time the orientation of the trunk and head respectively. The procedure based on this approach consists in giving acoustic feedback to the patients when they lose the control of a desirable orientation of the body. The range for a proper posture could be defined by the clinician at the beginning of the exercise, and the acoustic feedback, which is normally selected from disturbing sounds or alarms, alerts the child of the incorrect position. With this method, while the exoskeleton corrects the patients' gait, the postural control strategy motivates the children to maintain a proper posture during ambulation. This information provided by the biofeedback strategy was a request of our clinical partners since it is a parameter of paramount importance during the execution of the robotic therapy [96, 97, 159]. The exercises with IMUs supported the correction of the patient's crouched gait in order to achieve a better extended hip position, besides correcting the posture and improve motor control.

To monitor the orientation of trunk and head for the postural control strategy of CP-Walker, the information of both IMUs sensors (head and trunk) was sent to the clinician interface through rotation matrices (R, Equation 3.10):

$$R = \begin{bmatrix} X_x & X_y & X_z \\ Y_x & Y_y & Y_z \\ Z_x & Z_y & Z_z \end{bmatrix} \tag{3.10}$$

Each IMU sensor is referenced to the magnetic north and the maximum value of acceleration corresponds with z axis. This means that in order to measure rotations movements respect to an initial position, it is necessary to complete a calibration process [161]. During the execution of the therapy with CPWalker, the IMUs-based algorithm distinguishes between the rotation matrix collected at the time of calibration (R_G) and the rotation matrix captured by the IMU sensor in each instant (R_S). With these data, a new matrix (R_{GS}) for the reference system is calculated as Equation 3.11 indicates:

$$R_{GS} = R_S \cdot (R_G)^{-1} \tag{3.11}$$

The algorithm obtains the Euler angles (α, β and γ, related with rotation in frontal, sagittal and transversal planes respectively) using the Equations 3.12, 3.13 and 3.14 based on the development carried out in [161]:

$$\alpha = atan\left(-\frac{R_{GS}(2,3)}{R_{GS}(3,3)}\right) \tag{3.12}$$

$$\beta = asin\left(R_{GS}(1,3)\right) \tag{3.13}$$

$$\gamma = atan\left(-\frac{R_{GS}(1,2)}{R_{GS}(1,1)}\right) \tag{3.14}$$

In rest position, R_{GS} is the identity matrix and consequently, the Euler angles are equals to zero.

The information provided by the sensors is represented in real-time after undergoing the conversion algorithms. Figure 3.15-right shows an example of recording data in real-time from IMUs-based system, where the measured angles for head and trunk (blue lines) in three spatial planes were compared to the ROM of the left hip during walking (red lines). Red squares in Figure 3.15-left represent posture out of the permitted range (acoustic feedback playing).

3.2.3.1 Technical evaluation of the biofeedback strategy for postural control

The postural control therapy was preliminarily evaluated in one child with spastic diplegia in order to assess the usability of the system in clinical practice. The exercise consisted on using the biofeedback strategy for postural control at the same time than the user was walking following position control in the exoskeleton of CPWalker. The training lasted 5 sessions of 40 minutes each, one session/day. The main objective of this trial was oriented to assess the motor control improvements of the trunk during gait.

With the aim of objectively measuring the progress of the subject after this robot-based therapy, trunk kinematic data was obtained from 3D gait analysis before and after the experiment. The data collection was performed using an eight infrared cameras system (BTS BioEngineering, Italy). Reflective markers were applied on the shoulder girdle

Figure 3.15: IMUs based interface to give biofeedback of postural control in head and trunk. The graphics show IMUs data collected in real time for head and trunk in three planes (blue lines), and these were compared with hip ROM (red lines). The red squares represent postures out of the limit values (acoustic feedback playing).

(spinous process of C7 and both acromio-clavicular joints). Marker trajectories were processed and analysed. For comparisons, a pre-post graph was performed for the child (Figure 3.16). In this graph it is possible to see that post-training data (continuous lines) are closer to normal values (grey zone) than data from the pre-study (dotted lines). These preliminary outcomes reveal the potential of recovery of this strategy.

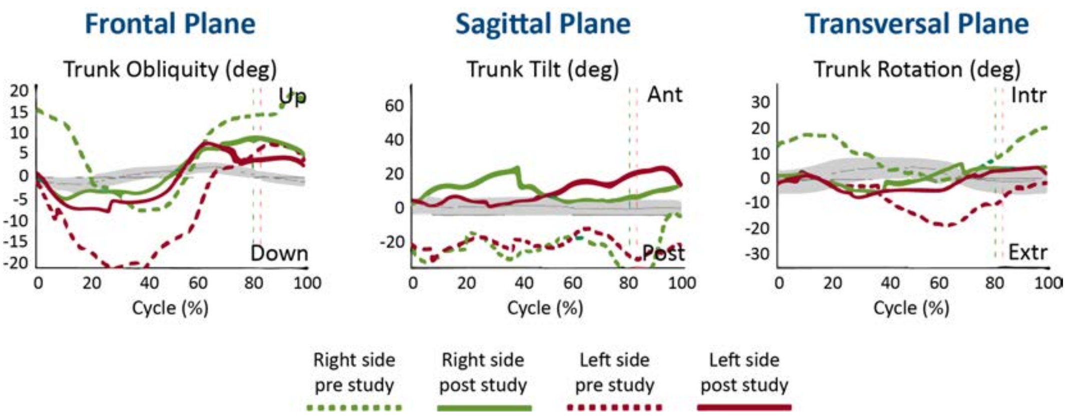


Figure 3.16: Patient's trunk kinematics during the pilot technical experiment. Normal trunk kinematics data is represented in grey. Pre-intervention data is represented through dotted lines. Post-intervention data is represented through continuous lines. Left side in red and Right side in green.

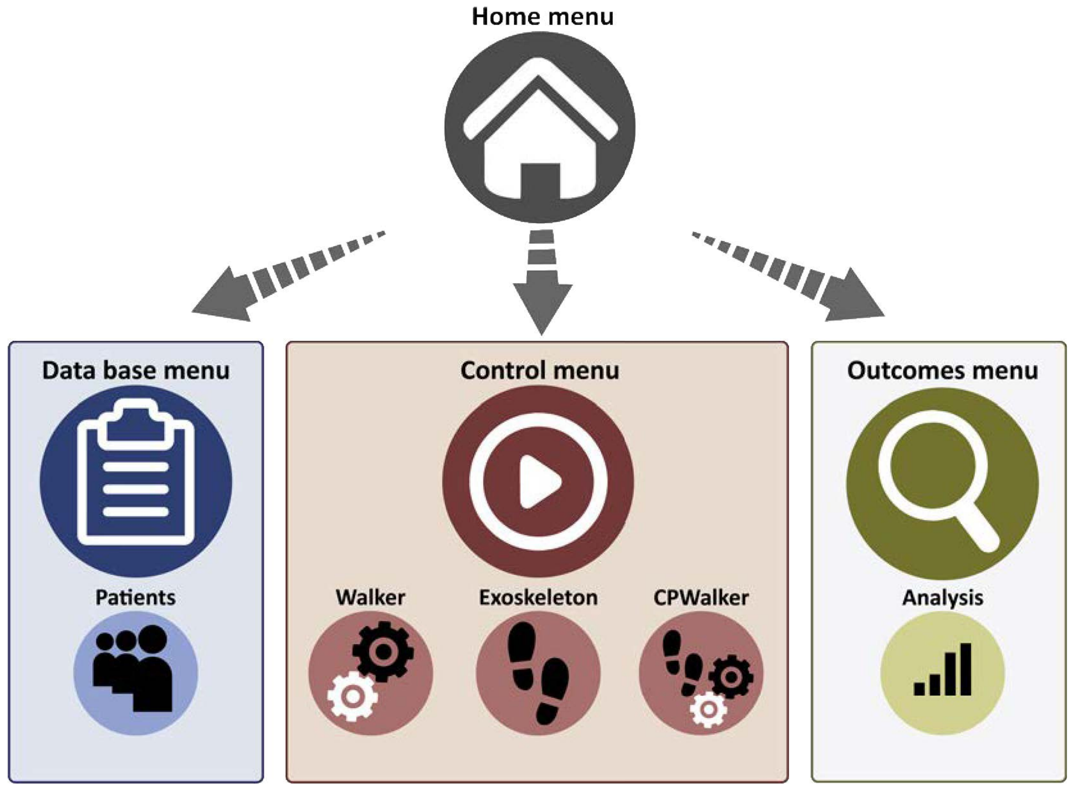


FIGURE 3.17: Schematic view of the methodology used for the CPWalker graphic interface.

3.3 Clinician interface of CPWalker

In order to facilitate the display and the interaction between the robot and the clinician, a graphic interface was developed. This interface allows the selection and evaluation of the different control strategies, as well as the parameters setting in real-time. The clinician interface consists of a tablet device that executes an application programmed for Windows 8.1. This unit monitors signals and tunes control parameters in real-time during the execution of the control strategy. It has the following main objectives: i) monitoring and validation of parameters for CP rehabilitation; ii) data analysis (statistics, algorithms performance, etc.); iii) storage of user's information such as clinical and anthropometrics data; iv) adjustment of the parameters of the therapy in real-time; and v) comparison between different robot-based rehabilitation therapies. Figure 3.17 shows a schematic view of the methodology used to implement the graphic interface of CPWalker.

The application to command the clinician interface (Figure 3.18) was developed with Visual Studio software, using Windows Form and C-sharp programming language. WiFi and UDP protocol are used to send the data to the control unit. This means that the application can transfer messages to other hosts (both PC104s) without prior communications to set up special transmission channels or data paths.

Figure 3.18 shows different screen-shots from the application of CPWalker. Its content is decorated with childhood drawings in order to be more appealing to the children. The current interface is very intuitive, developed with the aim of removing the frequent criticism from clinicians towards the difficulty and the required technical knowledge to often operate with robotic devices [43]. As Figure 3.17 showed, it is divided into three main menus (Data base, Control and Outcomes), which can be accessed from the Home Menu. Points below describe each main menu.

- **Data Base Menu:** this part is responsible of saving new user's information related with personal, clinical and anthropometrics data. It allows the therapist the possibility of having organized documentation about the patients who use CPWalker. This information is useful to tailor the therapy for a specific subject and to record data collected in each exercise in an orderly manner, classified by date, time and child's identification. The Patient's Data Base Menu also has the option of modifying existing data previously saved.

- **Control Menu:** the Control Menu is the most important part of the application. It provides the definition of therapies for each patient and its implementation in CPWalker. Before to specify the different parameters of the exercise, the therapist must choose an existing patient from the data base. Once the user has been selected, there are three possibilities of control: smart walker, exoskeleton or the complete CPWalker (smart walker + exoskeleton).

  The submenu to control only the smart walker gives the options of controlling the drive system by personal control or by using the LRF control [12, 145]. With the first option, is the clinician who chooses the speed of the displacement, while with the LRF control, this speed is determined by the recognition of patient's legs movement. With both controls is possible to save the data collected during the training.

  The submenu to control only the exoskeleton is used in first sessions of the rehabilitation process (when the user is completely suspended and therefore, the traction is not necessary). It has some fields to adjust the parameters of the therapy as: the type of control (position, force or impedance-high-medium-low modes), gait speed, ROM of gait pattern and number of steps. It also incorporates the possibility of using the BCI based on EEG system. Finally, within this submenu the therapist can also choose what joints wants to move, specifying an individual control for each of them. A button to save data during the gait training is also available here.

FIGURE 3.18: Windows of the Clinical Application developed to control CPWalker platform.

The submenu to control the whole platform is chosen when completed exercises are required (i.e. over-ground walking training with displacement through hospital facilities). The distribution of the components for this menu is similar to the one presented for the control of exoskeleton in the paragraph above. The main difference is that in this case the clinician can decide how much weight discharge is implemented by the robotic platform.

Every control menus have an available button to link the definition of the therapy with an interface to improve the patient's postural control.

- **Outcomes Menu:** this menu is used to analyse the recorded data of different therapies that have been made previously. The therapist has to choose one of the saved files specifying the patient's identification, date and time, and according to that, some graphics will be represented in a new window.

  The graphics provide information related to three fields: i) averaged performance of flexion-extension movements for hip, knee and ankle of both sides (right and left). This compares the averaged percentages achieved by the patient during all the therapy with the 100% required; ii) percentages of gait pattern, velocity and PBWS selected in the therapy associated with the selected file; iii) type of control that was chosen for each joint and data related to file information as date, time, patient or number of steps.

  This menu gives the opportunity of seeing the patient's progression and performance by an objective way and with clear information in order to select the variables for the next therapy. Quantifying and recording feedback content is very important because it effectively modulates motor learning and rehabilitation [162].

3.4 Preliminary locomotor training in pediatric population through CPWalker

Once each subsystem was evaluated in simulations, healthy subjects, or real patients, and an interface was developed for the therapist to control the robot, the next objective was to evaluate the concept of tailored-therapies depending on the patients' necessities. This section presents a preliminary locomotor training in pediatric population with spastic diplegia. The evaluation was implemented through the combination of different strategies defined in the previous points, solving each combination depending on the specific patient's needs. Concretely, the therapies designed in this preliminary study were defined with the aid of our clinical partners from HNJ, and were based on two key features: the IMUs-based interface to correct the user's posture during robot-assisted

Table 3.2: Description of the patients recruited for a preliminary clinical training with CPWalker robotic platform

Patient	Disease	GMFCS	Age (years)	Weight (kg)
P1	Spastic diplegia - CP	III	14	32
P2	Spastic diplegia - CP	II	12	40
P3	Spastic diplegia - HSP	-	13	43

walking, and the selective impedance control to achieve improvements of ROM for specific joints through the active collaboration of the patients'. Points below explain the patients' recruitment, therapy definition and the achieved outcomes after five weeks of treatment. These outcomes provided a preface to develop a future robot-based treatment protocol.

3.4.1 Patients

Three pediatric patients with spastic diplegia (one female), two suffering from spastic CP and one from Hereditary Spastic Paraparesis (HSP), were recruited to participate in this study (P1, P2 and P3 in Table 3.2). The inclusion criteria for the patient's recruitment were: i) capable of understanding the proposed exercises; ii) aged 11 to 18 years; iii) maximum weight 75 kg; iv) children with no deformations that could prevent the use of the exoskeleton; v) GMFCS levels I to III; and vi) abled to signal pain or discomfort. The exclusion criteria of this study were defined as: i) unhealed skin lesions in the lower limbs; ii) aggressive or self-harming behaviours; and iii) severe cognitive impairment.

The clinical trial was carried out at "Hospital Infantil Universitario Niño Jesús". The study was assigned the number R-0032/12 from the Local Ethical Committee of this hospital, and warranted its accordance with the Declaration of Helsinki. All patients and families were informed beforehand, and provided consent through parents to participate.

3.4.2 Therapy

The training with CPWalker was performed for five weeks, two days per week (10 training sessions), with the exercise time for each day set at 60 minutes, including 10 minutes of setup time. The exercises consisted of walking with the robotic device through routes in flat and straight lines into the hospital facilities.

The therapies were individually adapted for each patient aiming at enhancing the most affected region in each case. The criteria to select the most affected domain of each patient were in accordance to the results of gait assessments carried out before to start with robot-based therapies). Specifically, the treatment defined for P1 and P3 attempted to improve the postural control of the trunk during walking. As a result, a stiffer impedance control (position mode) of the lower limbs joints was set to assist the users' movement while they were more focused on posture control using the biofeedback strategy of CP-Walker (see section 3.2.3). In case of P2, the main purpose was to improve the ROM of the hip joint, primarily the extension movement. To perform this rehabilitation, a less stiff impedance control (medium impedance mode) of this joint was adjusted to intensify P2's collaboration in reaching the maximum extension of the hip. For this patient the biofeedback strategy for postural control was set with a bigger tolerance, which enabled the patient to be more focused on improving the hip movement. Given that these children had rigid AFOs, the ankle joints were fixed to 90 degrees. With no actuation on ankles, the propulsion on the ground was not high enough, so we imposed position control to knee joints in order to achieve a proper knee flexion.

With the aim of accommodating the patients to the robotic platform and following therapists' recommendations, all of them were completely suspended during the first sessions (PBWS of 100%), and the PBWS was gradually decreased along the course of five weeks of the study (e.g. Figure 3.19-yellow line for P1). This approach allowed the

FIGURE 3.19: Evolution of therapy parameters in P1. Blue line is the percentage of amplitude of the range of motion programmed in the robot. Yellow line corresponds to the percentage of the patient's body weight that is supported by the platform. These parameters were adjusted individually during the treatment in order to tailor the therapy to each patient.

Table 3.3: Selected parameters according to the patients' capabilities

	% ROM		**% PBWS**		**Gait velocity [m/s]**	
	Beginning	Desired End	Beginning	Desired End	Beginning	Desired End
P1	80	100	100	50	0.172	0.210
P2	85	90	100	60	0.159	0.210
P3	73	88	100	65	0.133	0.188

subjects to gradually get used to bearing their weight on their own legs. In the same way, the percent of ROM applied for each joint respect to a normal gait pattern (e.g. Figure 3.19-blue line for P1) and the gait speed were updated during the therapy with the purpose of increasing the difficulty of the exercise.

According to the pre-measured capabilities for each child and following recommendations from our clinical partners, the progression of the main parameters were selected before to start the robotic therapy (see Table 3.3).

In order to measure the patients' progression, 3D gait assessments without the aid of CPWalker were conducted before and after the robot-based therapy. These analysis provided kinematic data and temporal-spatial parameters that were used to evaluate the improvements of the therapy.

3.4.3 Results

After five weeks of robot-based training with CPWalker, the three children improved the mean velocity, cadence and step length (Table 3.4). Additionally, within the kinematic analysis, the three subjects progressed in their gait as Figure 3.20 and Table 3.4 show. Post-3D studies revealed that the trajectories for right and left lower limbs were closer to the normal values when compared to pre-3D studies. All children succeeded the goals proposed on Table 3.3.

As the therapies were individually tailored for each patient, the results have to be understood as separate case studies.

TABLE 3.4: Comparison between Pre and Post studies: spatial-temporal parameters and kinematics related to the selected improvements for each patient (correspondence with Figure 3.20). (*) corresponds to trunk rotation assessment and (**) to hip flexion-extension

Patient	Analysis	Side	Mean velocity (m/s)	Cadence (step/min)	Step length (m)	Kinematics: % Range (max-min)	Kinematics: Max. Peak (°)	Kinematics: Min. Peak (°)
	Normality		**1.20±.20**	**129.60±8.40**	**0.58±.06**	**100**	**4.80*/37.10****	**-2.40*/-2.40****
P1	Pre	Left	0.40±0	73.80±6.00	0.24±.04	278.71	0*	-15.42*
		Right			0.30±.01	286.29	14.83*	-2.92*
	Post	Left	0.49±0	75.80±7.97	0.27±.01	233.87	10*	-4.50*
		Right			0.33±.02	204.84	4*	-8.70*
P2	Pre	Left	0.60±.10	102.20±12.65	0.24±.05	85.82	48.40**	14.50**
		Right			0.31±.03	70.63	46.40**	18.50**
	Post	Left	0.80±0	120.80±9.38	0.38±.02	96.20	39.50**	1.50**
		Right			0.40±.01	95.19	41.90**	4.30**
P3	Pre	Left	0.20±0	45±3.70	0.30±.05	350.48	2.60*	-19.13*
		Right			0.23±.05	343.55	20*	-1.30*
	Post	Left	0.40±0	75±.60	0.33±.04	234.35	6.28*	-8.25*
		Right			0.32±.02	224.52	8.25*	-5.67*

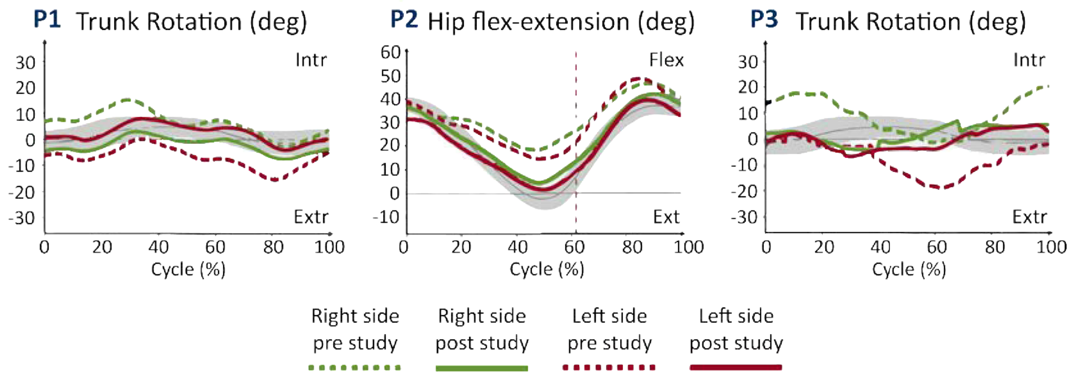


FIGURE 3.20: Outcomes from kinematic analysis in patients P1, P2 and P3 without robotic aid. The graphics show the improvements for each patient depending on the focus of each therapy. Green lines are referred to right side and red lines to left side. Dashed lines correspond to 3D studies done before the robotic treatment and continuous lines to 3D studies done after five weeks of robot-based therapy.

3.5 Application of the performance-based adaptive algorithm to LOPES II gait trainer

Within the mid-level of the framework for control strategies of CPWalker, the author proposed a new approach for adapting the robotic assistance based on user's performance (see subsection 3.2.2). This approach was also of important interest for other research groups, and indeed the author collaborated with the "Department of Biomechanical Engineering" at University of Twente (UT, The Netherlands), in order to apply the adaptive approach to the LOPES II robotic gait trainer [91]. This work was carried out during a research fellowship awarded by the Spanish Ministry of Economy and Competitiveness under contract EEBB-17-12035.

Several changes were implemented in the controller of CPWalker to adapt it to LOPES II. With the aim of providing the last advancements in relation with the assistive algorithm, and in order to develop new future therapies in CPWalker, this section presents the main improvements implemented in the performance-based adaptive algorithm and its preliminary implementation in LOPES II gait trainer [163].

3.5.1 LOPES II robotic trainer

LOPES II is a treadmill-based, admittance controlled robotic gait trainer that has eight actuated degrees of freedom (hip flexion/extension, hip abduction/adduction, knee flexion/extension, pelvis forward/aft and pelvis mediolateral) to control the motion of the lower limbs and pelvis [91]. It is primarily used for rehabilitation of stroke survivors and patients with SCI. The device is currently controlled through a graphical user interface in which the operator can manually adjust the level of robotic assistance for several subtasks of gait (i.e. step length, step height, stability during stance, prepositioning and weight shift). For each subtask, the assistance provided by LOPES II can be scaled from no support (minimal impedance mode) to 100% of support. These settings are maintained during a therapy session unless the therapist changes it.

Despite the existence of many differences between CPWalker and LOPES II (e.g. device purpose, over-ground training vs treadmill, children vs adults rehabilitation...), the background for the control of both robotic platforms is very similar. According to that, the performance-based adaptive algorithm presented in subsection 3.2.2 was adapted through some improvements to be applied in LOPES II, with two main goals: i) to enrich the current robotic rehabilitation supporting the physiotherapists with novel objective tools; and ii) to test the potential of this controller as an assessment tool for rehabilitation.

3.5.2 Improvements of the performance-based adaptive algorithm

Figure 3.21 represents the new scheme of the adaptive controller adjusted for LOPES II. Comparing this scheme to the one developed for CPWalker (remember Figure 3.13), it is possible to observe several changes, which were introduced in order to improve the previous algorithm and to adapt it to the LOPES II control architecture. The most important improvements are described below.

3.5.2.1 Subtask-based besides joint-based

In CPWalker, the adaptive algorithm evaluated user's performance for each joint ROM (i.e. the new assistance, updated based on the performance, involved the whole gait cycle for each joint). In that sense, the equations used to calculate the performance (Equations 3.5 to 3.7), took into account the average of the user's behaviour reaching specific key points of the gait cycle (Equation 3.8, maximal flexion-extension angles). However, for LOPES II, this evaluation was improved in order to be subtask-based besides joint-based (Figure 3.21). The subtasks were classified in: step height, stability during stance, prepositioning and step length.

To calculate the performance for different subtasks of walking within each joint, author used the same concept of key points of the gait cycle, localizing each subtask in one of these points (see black dots in *Performance-based evaluation* box of Figure 3.21). The equations to calculate the new subtask-based performances ($Perf_j$) were modified from the previous algorithm, normalizing the deviations from the reference pattern as

FIGURE 3.21: Overview of the performance-based adaptive controller adjusted for LOPES II gait trainer. User's performance is evaluated based on the difference between measured (θ) and reference (θ_{ref}) joint angles for each subtask j and in each leg separately, looking at some "key points" of the gait cycle (deviations at black dots in "Performance-based evaluation" box). The performances per subtask are compared to the challenge and tolerance ($\Psi \pm tol$) after a specific number of steps ($T_{evaluation}$), and based on this, a new level of assistance ($k_{level,j}$ from 0% to 100%) is applied for each subtask. Depending on the subtask of gait that is assisted, specific assistance profiles are applied by the robotic gait trainer (green lines in "Subtask-based profiles" box).

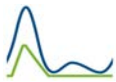
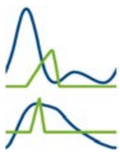
Equation 3.15 indicates. In Equation 3.15 "j" is the subtask, G_j is a subtask-specific gain, θ_{ref} and θ (expressed in radians) are the reference and measured angles at the subtask-specific key points, and "n" is the number of previous steps in which the performance was evaluated (also called time of evaluation $T_{evaluation} = n$):

$$Perf_j = G_j \cdot \left(\frac{\sum_{i=1}^{n} (\theta_{ref,j})_i - \sum_{i=1}^{n} (\theta_j)_i}{n} \right) + 100 \tag{3.15}$$

Table 3.5 shows the assistance profiles, key points locations and gains (G_j) to apply Equation 3.15 for each subtask. The specific gains were defined based on acceptable deviations from the normal reference gait pattern of previous pilot studies conducted with healthy users using LOPES II. As Table 3.5 shows, gains are negative or positive depending on the supported movement (flexion and extension respectively). According to this and following the concept implemented in CPWalker, users' performance was penalized if they did not reach the reference pattern, but not if they overcame it.

Once the performance is calculated for each subtask "j", it is compared to the challenge in order to update the robotic assistance per subtask (k_j). The assistance profiles depended on the subtask that was supported (see green lines in the *Subtask-based profiles* box of Figure 3.21 or "Profile" column in Table 3.5). Any combination of assistance profiles was

Table 3.5: Supported movements and gains for diverse subtasks of gait to calculate performances using Equation 3.15. Assistance profiles (green lines) applied for each subtask are shown with respect to the joint angle for hip or knee (blue lines).

Subtask	Profile (green line)	Supported movement	Key point location	Gain (G_j)
Step height		Knee flexion	Maximal knee flexion	-175
Stability		Knee extension acceptance	Knee weight acceptance	300
Prepositioning		Knee extension and hip flexion late swing	Maximal knee extension late swing	250
Step length		Hip flexion	Maximal hip flexion	-300
		Hip extension	Maximal hip extension	350

possible, which means that the user could receive robotic assistance for various subtasks and both legs simultaneously.

3.5.2.2 Tolerance zone around the challenge

One of the main limitations of the adaptive algorithm of CPWalker was that the level of assistance continuously changed after each group of “n” steps. This fact caused a high variability within the control modes and therefore, the user could not get used to walk with a concrete assistance.

To address this issue in LOPES II, a tolerance (tol) zone was added around the selected challenge. Based on this, the robotic assistance per subtask of gait was also automatically adjusted each group of “n” steps, but in that case by offering the possibility of maintaining the previous value. It might be affected in different ways: first, if performance was within a specific range around the previously selected challenge, amount of robotic assistance in the particular subtask remained constant; and second, assistance increased or decreased depending on whether the performance was below or above the specified range respectively (see Equation 3.16).

$$\begin{cases} Perf_j < \Psi - tol & \Rightarrow \uparrow k_{level,j} \\ Perf_j > \Psi + tol & \Rightarrow \downarrow k_{level,j} \\ \Psi - tol \leq Perf_j \leq \Psi + tol & \Rightarrow = k_{level,j} \end{cases} \tag{3.16}$$

3.5.2.3 Six levels of assistance

In CPWalker, the mechanical support of each joint was classified as one of the possible control modes (P, HI, MI, LI or F) implemented in the robotic trainer. In case of LOPES II, the robotic assistance was classified into six discrete levels of support (from 0 to 100% with steps of 20%). The author together with other colleagues from UT considered this number of levels enough to provide the required assistance, also making it easier to interpret when the controller is used for assessment. Assistance levels per subtask went either one level up or down or remained constant based on Equation 3.16.

3.5.3 Preliminary implementation

Walking speed and PBWS are two parameters that often change during gait training in people with neurological disorders. These variations could became confounding factors for assessment, and hamper reliable measure of walking impairments [164, 165]. To design future training protocols, it is very important to understand whether walking guidance provided by the robotic trainer is affected by gait speed and PBWS [164]. Moreover, these parameters are crucial to evaluate the feasibility of the controller not only for training but also for the assessment of patients' abilities.

3.5.3.1 Participants

In order to study these effects of amount of walking speed and PBWS on the assistance provided by the adaptive AAN algorithm applied in LOPES II, ten volunteers without neurological, muscular or orthopaedic problems were recruited to participated in this study (seven male, three female, weight 72.79 ± 12.11 kg, height $1.80 \pm .07$ m and age 26.3 ± 2.36 years). The protocol was approved by the Medical Ethical Committee Twente (The Netherlands), and all subjects were informed about the experiment and signed informed consent forms.

TABLE 3.6: Overview of trials to test the effects of walking speed and PBWS on the behaviour of the adaptive controller in LOPES II.

Task	Speed (m/s)	PBWS (%)	mImp (min)	rAAN (min)
T0	0.3	0	5	-
T1		0	1.5	3
T2	0.2	20	1.5	3
T3		40	1.5	3
T4		0	1.5	3
T5	0.4	20	1.5	3
T6		40	1.5	3
T7		0	1.5	3
T8	0.6	20	1.5	3
T9		40	1.5	3

3.5.3.2 Protocol

LOPES II was fitted to each user and attached to the user's lower legs and feet. Subsequently, the harness was fixed to the pelvis and trunk to provide fall protection and PBWS.

The protocol consisted of several trials (T0-T9) presented in Table 3.6. Participants firstly walked at 0.3 m/s without robotic assistance and no PBWS to become used to walking in LOPES II (T0). The order of the rest of the trials (T1-T9) was randomized for each participant, considering every possible combination of three gait speeds (0.2, 0.4 and 0.6 m/s) and three levels of PBWS (0%, 20% and 40%). In all of these trials, participants walked for 1.5 minutes in minimal impedance mode (no assistance, see mImp column in Table 3.6), followed by 3 minutes in which the adaptive AAN controller was turned on (rAAN column in Table 3.6). A challenge of 80 was used with a tolerance of ±5 (equation Equation 3.15 and Equation 3.16, $\Psi \pm tol = 80 \pm 5$). Subjects were blinded to the robotic assistance, as they did not receive any information on the provided assistance to minimize bias.

3.5.3.3 Analysis

Hip and knee joint angles, step length, user' performances and received robotic assistance were analysed for the abovementioned subtasks of gait, and compared between the various walking speeds and amounts of PBWS.

Author conducted statistical calculations using IBM SPSS Statistics v.23 (IBM, United States). Two-way repeated measures ANOVA were applied to evaluate differences in the performances per subtask for the SPEED (3 levels) and PBWS (3 levels) during minimal impedance mode (no assistance). This period without assistance was chosen to prevent that the robotic assistance resulting from the adaptive controller influenced the performances and the results from the statistical analysis. Pairwise comparisons with Bonferroni corrections were applied for all main effects and interactions that were significant for the repeated measures ANOVA.

3.5.3.4 Results and discussion

As the experiments were performed on healthy participants, similar results were found for both legs. Therefore, I only show the results for the participants' right legs.

Effects on kinematics: As the reference gait trajectories for LOPES II were only adjusted based on walking speed but not for PBWS [151], author and colleagues from UT focused on differences in kinematics between the different levels of PBWS. Figure 3.22 shows averaged changes on measured joint angles depending on the amount of PBWS when no assistance was applied at 0.4 m/s. Maximal hip flexion and extension angles decreased when the amount of PBWS increased (see hip joint in Figure 3.22). Similar results were found for the other walking speeds. These decrements in maximal hip flexion and extension resulted in shorter step length for larger amounts of PBWS (Figure 3.23). For the knee joint, author found a decrease in the knee flexion peak for an increased amount of PBWS (Figure 3.22). In contrast, more knee extension at heel strike was achieved for larger amounts of PBWS.

Effects of walking speed and PBWS on the users' performance without robotic assistance: The changes in joint angles when no robotic assistance was applied also led to changes in the performances calculated with Equation 3.15 (see unfilled boxplots of Figure 3.24). Performances for step length (hip flexion and extension) and step height (knee flexion) decreased when PBWS increased. In contrast, performances for prepositioning and stability (knee extension) increased when more PBWS was applied. Two-way repeated measures ANOVA confirmed significant effects of PBWS for all subtasks-based performances (Table 3.7). Moreover, two of five subtasks also showed significant effects of walking speed.

The fact that gait performances were significantly affected by PBWS is in agreement with previous studies about changes in kinematics with PBWS [164, 165]. However,

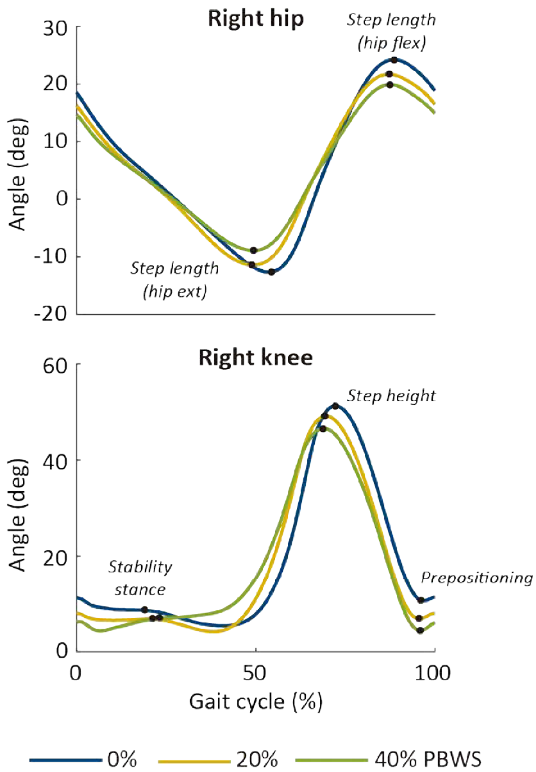


Figure 3.22: Effects of various amounts of PBWS on mean joint angles for ten healthy users walking at 0.4m/s when no robotic assistance was provided. Black dots indicate key points for each subtask.

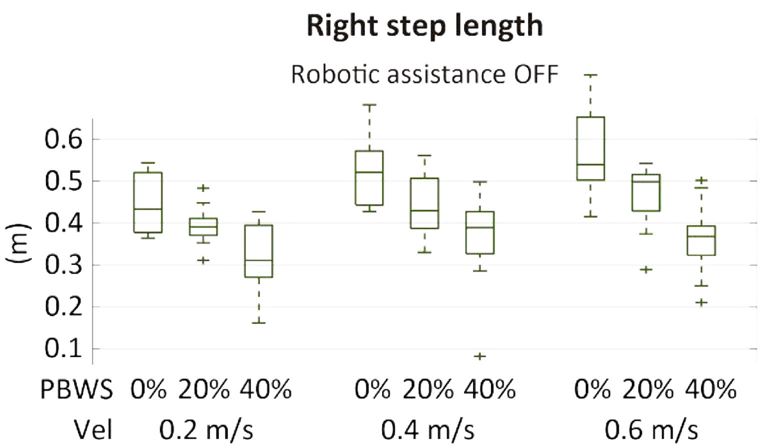


Figure 3.23: Effects of various amounts of PBWS on right step length for ten healthy participants when no robotic assistance was provided.

TABLE 3.7: p-values for the 2-way repeated measures ANOVA for each subtask of gait. (*) indicates significant differences with $p < .05$ and (**) significant differences with $p < .001$.

Subtask	Speed	PBWS	Speed*PBWS
Step height	.799	.018*	.525
Stability during stance	.023	.021	.085
Prepositioning	.261	.004	.748
Step length (hip flexion)	.451	.000**	.057
Step length (hip extension)	.003	.000**	.714

these previous studies mainly found significant changes when PBWS was 50% or higher, while we already found significant differences in performance for PBWS lower than 50%. A possible reason for this might be that participants in our study walked in a robotic gait trainer, while participants in other studies walked freely on a treadmill.

Pairwise comparisons showed the following significant differences (p¡.05) for PBWS: between 0% and 20%: step length (hip flexion (p=.001) and extension (p=.040)), step height (p=.019) and stability during stance (p=.032); between 0% and 40%: step length (hip flexion (p=.001) and extension (p=.033)), step height (p=.038) and prepositioning (p=.016); and between 20% and 40%: step length (hip flexion (p=.003) and prepositioning (p=.024). In case of walking speed, significant differences (p¡.05) in performances were found between 0.2 m/s and 0.6 m/s for step length (hip extension (p=.033); and between 0.2 m/s and 0.4 m/s for knee stability (p=.005) and step length (p=.040).

Effects of walking speed and PBWS on the performance-based adaptive controller: The controller gave good response, adapting robotic assistance in case that was required. However, as expected, most participants did not receive much robotic assistance, as their performances were larger than the selected challenge of 80. For this reason, medians of robotic assistance (red boxplots in Figure 3.24) are close to zero for most trials. Further experiments with people with neurological disorders are needed to evaluate the performance of the controller.

Only the performance of some subtasks in a limited number of participants and conditions was lower than the selected challenge of 80 minus the tolerance ($Perf_j < 80 - 5$). In these cases, the controller increased the robotic assistance that was provided to the users (see red boxplots in Figure 3.24) to improve the gait performance per subtask (blue boxplots in Figure 3.24). For example, in T1 (0.2 m/s and 0% PBWS), gait performance was very low for knee stability when no assistance was applied (unfilled blue box for this condition of knee stability in Figure 3.24). However, when the controller was turned on, gait performance increased for this condition as the participants received robotic assistance (filled blue box for same condition in Figure 3.24).

The results indicated that the new controller cannot directly be used as an assessment tool as the performances depended on the levels of PBWS and walking speed. Changes in performance and assistance during therapy might be falsely attributed to changes in patients' capacities whereas they are actually caused by changes in PBWS or walking speed. This means that it is necessary to maintain the control for PBWS and walking speed when making comparisons within patients, or the references trajectories need to be improved including the dependencies on PBWS. However, in the latter aspect, it might be difficult to do this, as the speed dependencies are already incorporated and the results also shown effects of speed. Nevertheless, the controller could be used as a tool to monitor progression during therapy and to improve RAGT by helping physiotherapists to tailor the exercises to the capacities of a specific patient. Decrements in robotic assistance required by a patient who walks at a specific amount of speed and PBWS, might be treated as a measure of walking improvements.

In future studies, the adaptive controller will be tested in stroke survivors to get more insight into its capacities as a monitoring tool during therapy after stroke and as a therapeutic tool after neurological disorders.

3.6 Conclusions

According to the main objectives of this chapter, it presented the principal components of the MHRI, and different control strategies for gait rehabilitation through CPWalker robotic platform were designed and implemented. The modularity of the robotic trainer was evidenced in order to adapt the robot to the patient's needs. Beyond the trajectory tracking, other AAN strategies were exposed, as well as a method to improve the postural control for over-ground training. All the control strategies were conceived in the development of a clinician interface to command the exercises.

The major contribution of this chapter has been the definition of novel control strategies using diverse technologies and their integration. This fact differs from the current robot-based therapies in which none of the robotic trainers for gait rehabilitation in pediatric population includes as many possibilities as were exposed here. All the strategies were technically validated and, furthermore, a previous clinical validation with three patients was presented. The multi-joint adaptive algorithm for performance-based therapies gave the great advantage of tailoring the exercise in real-time. This algorithm was also implemented and evaluated in LOPES II gait trainer with the goal of improving the current robotic therapies in stroke survivors and testing the influences of walking speed and PBWS on gait performances.

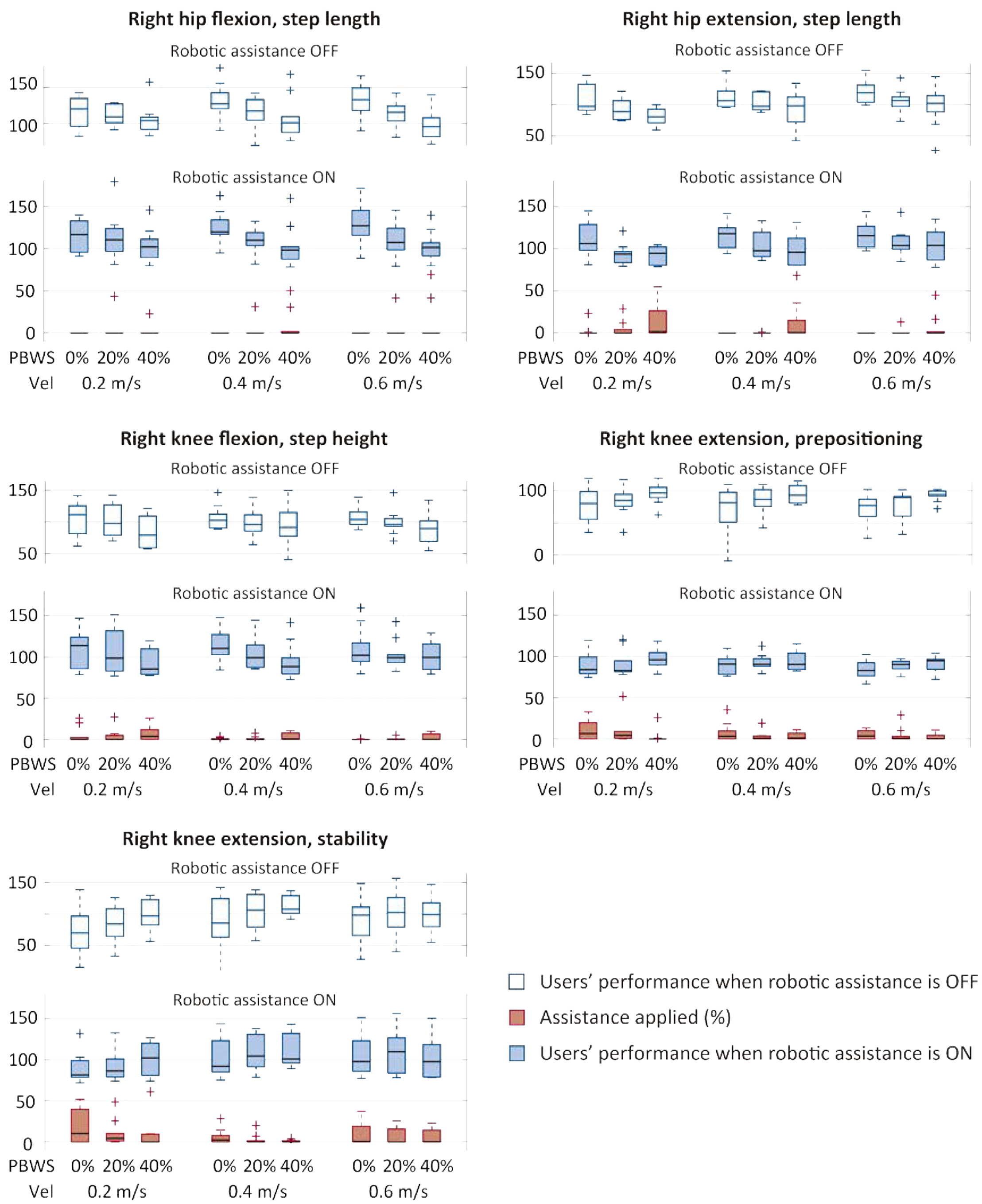


FIGURE 3.24: Gait performances determined with (1) in ten healthy users for diverse subtasks of walking in two situations: i) when no robotic assistance is applied (unfilled blue boxes), and ii) when the performance-based controller applied robotic assistance (filled blue boxed). The applied robotic assistance is represented in % (red boxes). Within each subtask, various amounts of gait speed and PBWS were evaluated.

Previous results from preliminary validations showed the importance of considering novel robot-based strategies through CPWalker into gait rehabilitation. The major strength of the robotic platform is the capability of selecting individual AAN control modes per joint in over-ground displacement while the apparatus provides feedback in order to correct the child's posture. These functions enabled the definition of tailored therapies for each patient.

Although preliminary outcomes are quite promising, the population size of the exposed pilot trials, the reduced time of intervention and the short-term follow up are the main limitations of this research. In the next chapter, CPWalker robot and some of its control strategies will be evaluated in real pediatric patients with CP following a defined clinical protocol, which is based on the tests exposed here.

Chapter 4

Gait Training Proposal: Goal Setting, Clinical Implementation, Results and Discussion

Although the use of robotic trainers has increased with the aim of improving gait function in patients with limitations, there is an absence of studies that deeply describe detailed guidelines of how to correctly implement robot-based treatments for gait rehabilitation. The aim of this chapter is to propose an accurate robot-based training program for gait rehabilitation of pediatric population with CP. This will serve to provide resources to facilitate the implementation of robotic therapies into the clinical practice.

The rehabilitation program was focused on the achievement of some specifications defined by the International Classification of Functioning, Disability and Health framework, Children and Youth version (ICF-CY). It was framed on 16 non-consecutive sessions where motor control, strength and power exercises of lower limbs were performed in parallel with a postural control strategy. A clinical evaluation with four pediatric patients with CP using the CPWalker robotic platform is presented.

The improvements achieved in short-term show the importance of working strength and power functions meanwhile over-ground training with postural control. This research could serve as preliminary support for future clinical implementations in any robotic device.

This study was carried out with the number R-0032/12 from Local Ethical Committee of the Hospital Infantil Niño Jesús [14]. Public trial registration: ISRCTN18254257.

4.1 Robot-based gait training therapy

As the previous chapters have exposed, gait limitation is one of the main impairments in children with CP [25]. This mobility deficiency in CP is commonly the consequence of a damage of the child's CNS, and an optimal functional training is required in order to maximize the improvements [166], which will highly contribute to the enhancement of the independence and, therefore, the quality of life for both the young patient and his family [6].

The use of robotic trainers for neurorehabilitation applications has increased in the last decades, both in adulthood and childhood, and in several motor diseases [3, 6, 167]. Robot-based therapies have been developed and improved beyond reducing the clinician's effort. Currently, a new generation of robotic devices [12, 84, 112] provides means for encouraging the patients to an active participation in exercises, which are now more task specific. Both the implemented novel control strategies and the modularity of new exoskeletons and gait trainers offer promising possibilities to enhance the rehabilitation outcomes by adapting the treatment to the patient's needs [13, 168]. Nevertheless, so far there is not enough evidence to ensure that classic robot-based rehabilitation provides better treatment outcomes by itself than conventional physical strategies in childhood [8]. The intention of CPWalker platform is to support these common physical therapies, working in parallel with them and taking advantage from both methods, robotic and non-robotic. Nevertheless, in this sense new approaches are needed in order to improve the rehabilitation, making the robotic therapy a key feature of the change.

One of the main drawbacks for the everyday use of robotic technologies into the rehabilitation practice, apart from the price of the devices, is the absence of studies that describe a detailed robotic training program for gait rehabilitation. The wide variety of changes that could be applied to the parameters of robotic training therapies, makes unclear how to specify rehabilitation settings with the aim of providing a suitable solution for a large population size. Additionally, most of current studies are only focused on lower limbs strategies. However, the upper body (head and trunk movement) also influences gait function through walking balance [88], so a proper program should not ignore these features.

This chapter presents a detailed robot-based therapy proposal for the rehabilitation of gait function in children with CP, which is based on the achievement of some specifications defined by the International Classification of Functioning, Disability and Health framework, Children and Youth version (ICF-CY) [16]. It contributes with better answers on how to implement robotic rehabilitation following defined guidance, establishing the baseline settings and subsequently tailoring the therapy to each patient.

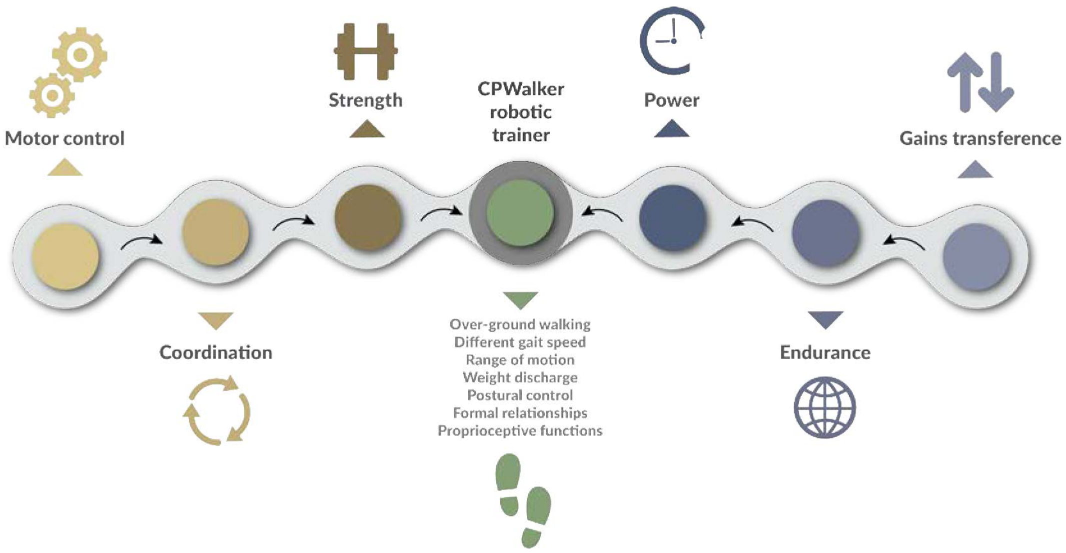


FIGURE 4.1: Overview of the training protocol and main gait functions that need to be covered.

The proposed robotic program was elaborated together with the advice of Dr. Gaebler at Rehabilitation Institute of Chicago (RIC, United States), and it works around a key factor: the implementation of strength and power exercises at the same time than over-ground walking guidance, performing in parallel an active head-trunk control therapy. As a result, the robot-based program recreates a situation as similar as possible to a real gait scenario, and encourages the patients to control different movements associated with gait: not only individual movements of lower limb joints, but also the synergy between them while maintaining a proper posture of upper body. The hypothesis is that these essential components, performed following an appropriate progression of the variables, will boost the patients' rehabilitation. Figure 4.1 represents the main functions that author tried to cover with the proposed treatment. It was based on the possibilities offered by CPWalker, but the objective was that these guidelines could be used on other gait rehabilitation platforms.

At the end of the chapter, the proposed robot-based therapy is evaluated in four patients with CP in order to provide preliminary results of its application. CPWalker training platform [12] was selected as scenario to test the effectiveness of the approach since it already provided means for adapting the therapy to the user's necessities through different levels of assistance in multi-joint over-ground training.

4.1.1 Robotic training program

In order to define the objectives of the robot-based treatment, the conceptual framework of ICF-CY [16] was adopted. The proposal was focused on improving the principal gait-related functions derived from this international classification. Concretely, the selected goals of the ICF-CY to be achieved with the treatment and the work methodology implemented in the robotic device, are presented in Table 4.1.

To achieve the goals presented in Table 4.1, a systematic selection of variables based on the requirements of the National Strength and Conditioning Association (NSCA) youth training guidelines was previously performed [169], which suggests that eccentric and explosive strength exercises should be the beginning of a proper training to ensure greater muscle power generation and the transference of gains to gait (Table 4.2).

According to the proposed objectives (Table 4.1) and complying with the NSCA youth training guidelines (Table 4.2), the treatment was conceptualized into two main *phases*, where the ROM, PBWS and gait velocity were the principal parameters under variation. The intention was that the patient maximized the gains acquired in the whole rehabilitation period (ideally the sum of robot-based exercises and common non-robotic therapy). A detailed description of each *phase* follows:

- *First phase*: the main aim of this *phase* was to improve motor control, teaching the patients the correct sequence of motion and increasing strength. The patients were requested to follow the movements established by the exoskeleton with the minimal possible resistance during swing period, pushing the ground at each step and trying to keep the maximum flexion-extension values at the end of each gait cycle. Instructions were given to ensure the comprehension of normative gait patterns, and verbal encouragement in addition to direct feedback by graphics in real-time was delivered throughout the sessions.
- *Second phase*: the main aim of this phase was to further train motor control and increase power in order to ensure the transference to the independent gait pattern. Aware of the sequence of movement of a normal gait pattern, the patient's contribution became an important aspect to develop neuroplasticity and preserve the gained motor control [146]. The active participation was achieved both by boosting the patient's motivation and by requiring self-activity [85]. The latter was implemented through AAN algorithms based on the impedance control modes presented previously for CPWalker in chapter 3.

Figure 4.2 represents the schematic view of the therapy proposal. The treatment was composed of a total of 16 sessions (*first phase*: 8 sessions for strength training and

TABLE 4.1: Goal settings of the ICF-CY and the robot-based solutions adopted with CPWalker platform

ICF-CY functional domain [16]	**Implementation on CPWalker**
Mobility and stability of joint functions (b710, b715)	The different control modes of the exoskeleton are used to guide the movement of a single or multiple joints, improving motor control. The exoskeleton also helps to maintain stability through the coordinated actions of surrounding tissues. This domain is exercised along the whole treatment with diverse robotic assistance.
Muscle power functions (b730)	The *second phase* of the training requires the patient to contract a muscle or muscle groups to generate the necessary force in order to start and maintain the movement with AAN strategies. The force must be maintained for a time in the extremes of the gait pattern (maximum flexion and extension) in order to reach the these maximum values in the complete ROM.
Muscle endurance functions (b740)	Muscle endurance is exercised when the patient is requested to sustain a muscle contraction to finalize the required movement with AAN strategies, mainly in the extremes of the gait pattern (maximum flexion and extension).
Control of voluntary movement functions (b760)	The voluntary movement is implemented through the control and coordination of simple and complex movements to collaborate with AAN strategies. Lower impedance implies more patient's control.
Gait pattern functions (b770)	Motor control and gait pattern functions are trained through the different control modes to guide the lower limbs following prescribed gait patterns at several velocities and supports.
Maintaining a body position (d415)	A biofeedback strategy for postural control is used to notify the patients when they lose the correct position of the upper body. See section "Postural control".
Walking (d450)	Over-ground walking training is executed in all sessions with controlled PBWS, at different velocities and supports.
Proprioceptive functions (b260)	During random moments of the first training session, the patients perceive feeling using a mask on the eyes at the same time than the robot performs the movement for single or multiple joints with 100% of PBWS.
Formal relationships (d740)	Creating and maintaining patient-researcher relationship. See section "Motivation and inclusion of challenges".

TABLE 4.2: National Strength and Conditioning Association (NSCA) youth training guidelines

ADAPTED YOUTH RESISTANCE TRAINING NSCA GUIDELINES		
Variables	**Strength**	**Power**
Muscle actions	Eccentric/Concentric	Eccentric/Concentric
Exercise	Single/Multi-joint	Single/Multi-joint
Intensity	$\uparrow$ Load/$\downarrow$ Velocity	$\downarrow$ Load/$\uparrow$ Velocity
Velocity	Moderate	Moderate/Fast

motor control learning; and *second phase*: 8 sessions to transfer the gains to gait through power performance). Exercises were multi-joint and gait-oriented, demanding concentric-eccentric actions based on the gait *phase* that was being performed. During the whole treatment (*first* and *second phases*) the position of head and trunk during walking exercises were monitored, especially because these patients usually walked looking at the ground. For this purpose, the strategy for postural control of CPWalker encouraged the patients giving an acoustic feedback when their position was inappropriate, so they could realize and rectified it by themselves. The program was reinforced with modifications on AAN levels according to the patient's evolution, based on performance evaluations related to ROM, PBWS and gait velocity. Furthermore, several challenges were included to enhance the patients' motivation.

4.1.1.1 Duration of the study

The robot-aided treatment was proposed for a whole period of 2 monthly cycles (one month for each *phase* of the treatment) with the aim of having enough sessions to generate significant neural changes [170]. The children trained 2 non-consecutive days per week for 8 weeks (16 sessions, see Figure 4.2). The sessions consisted of a 10-15 minutes warm-up and 60 minutes of over-ground exercise with CPWalker, including 3 minutes of independent gait as a cool-down phase. As Figure 4.2 indicates, the first 8 sessions corresponded with general motor control and strength exercises, where the robot imposed a gait trajectory tracking. Sessions 9 to 16 were related to muscle power performance through levels of AAN strategies, where self-activity was required.

4.1.1.2 Training phases

In order to individually define the training progression through the different sessions and to comply with the NSCA guidelines, the principal modifications were implemented on

FIGURE 4.2: Robot-based training program overview. *First phase*: sessions S1 to S8 for strength exercises where motor control was primary trained. *Second phase*: sessions S9 to S16 for power training where the assistance was progressively decreased with the patient's progression. The improvements were assessed at three stages of analysis: before treatment begins, between both phases and at the end of the program (grey ellipses in the figure).

ROM, PBWS and gait velocity. The selected parameters for both *phases* are represented by Figure 4.3 and Figure 4.4 respectively. This selection was concluded in collaboration with the clinical partners of the HNJ, based on the evaluation of previous studies carried out with CPWalker [13, 171]. The robot-based tasks began with high assistance and PBWS, and they progressed toward greater ROM and smaller PBWS as long as the patient overcame the different levels of the sessions. Parameter variations within and between sessions were performed as long as session goals were attained and when the clinical staff agreed, based on levels of spasticity, fatigue and motor control presented in the last day. If the patient was not ready to jump to the next challenge, the session was repeated with the same last percentages.

Within the *first phase* (Figure 4.3), the first session was performed with the children completely suspended (100% of PBWS) in order to adapt the users to the movements with the robot. Moreover, during random moments of this first session, the patients wore a mask on their eyes to feel the motion performance (Figure 4.5-b); in other occasions, a visual feedback of motion performance was represented on a screen in order to integrate the child into the therapy making easier the understanding of motor control (Figure 4.5-a). For the rest of the *first phase* children's lower limbs were guided through a pure

FIGURE 4.3: *First phase*: strength training progression values along first 8 sessions of the robot-based therapy. Trajectory tracking motion was imposed by the robot. Blue line represents the movement amplitude (%ROM), yellow line gives the changes of %PBWS and the green line is referred to gait velocity percentage for each session.

position control imposed by the CPWalker platform, with a gradual decrease in PBWS (Figure 4.3 yellow), and a gradual amplification of ROM (Figure 4.3 blue). Gait velocity during this *first phase* was maintained around a regular and small value (Figure 4.3 green). Notice that in general, only one variable at each session was varied.

The *second phase* of the training (sessions 9 to 16 in Figure 4.4) presented an additional difficulty that enhanced the user's collaboration in the exercises performance through different levels of AAN strategies in the exoskeleton. The initial ROM for the *second phase* was set at 80% of the total gait pattern and reached 100% by session 13 (Figure 4.4 blue), time at which velocity was highly increased (Figure 4.4 green). Note that gait velocity for this *phase* became around double of the one achieved in the *first phase*, which is in relation to the requisites exposed in Table 4.2. Furthermore, PBWS declined up to 30% of weight supported by the platform (Figure 4.4 yellow).

It is important to highlight in Figure 4.3 and Figure 4.4 that the percentage of PBWS was related to the individual patient's total weight, and the percentage of ROM was applied to the total trajectory of the gait pattern programmed in the control of CPWalker [12]. The estimated changes in gait velocity are represented regarding percentages of CPWalker platform, where 100% corresponded to 0.6 m/s.

Tailored Assist as Needed strategies: With the aim of enhancing the patient's participation in the *second phase* and consequently improving outcomes of the treatment,

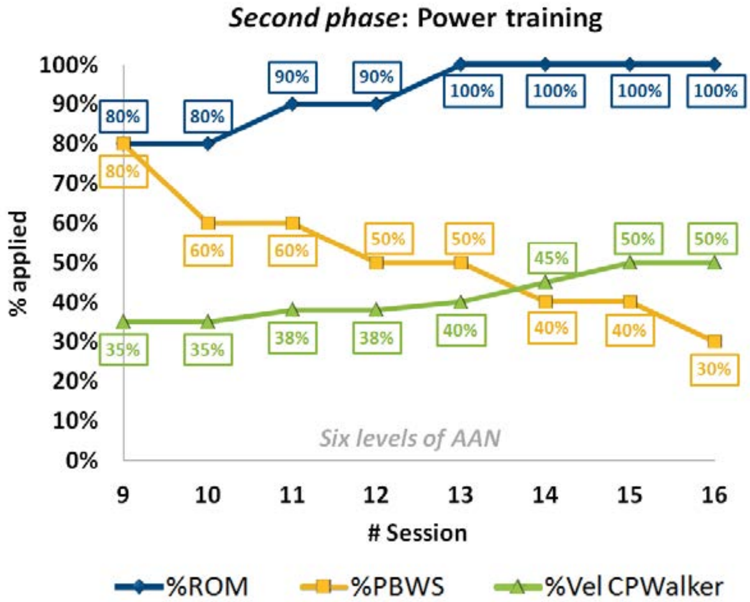


FIGURE 4.4: *Second phase*: power training progression values along sessions 9 to 16 of the robot-based therapy. Six different levels of assistance were selected on the exoskeleton (combining hips and knees). Blue line represents the movement amplitude (%ROM), yellow line gives the changes of %PBWS and the green line is referred to gait velocity percentage for each session.

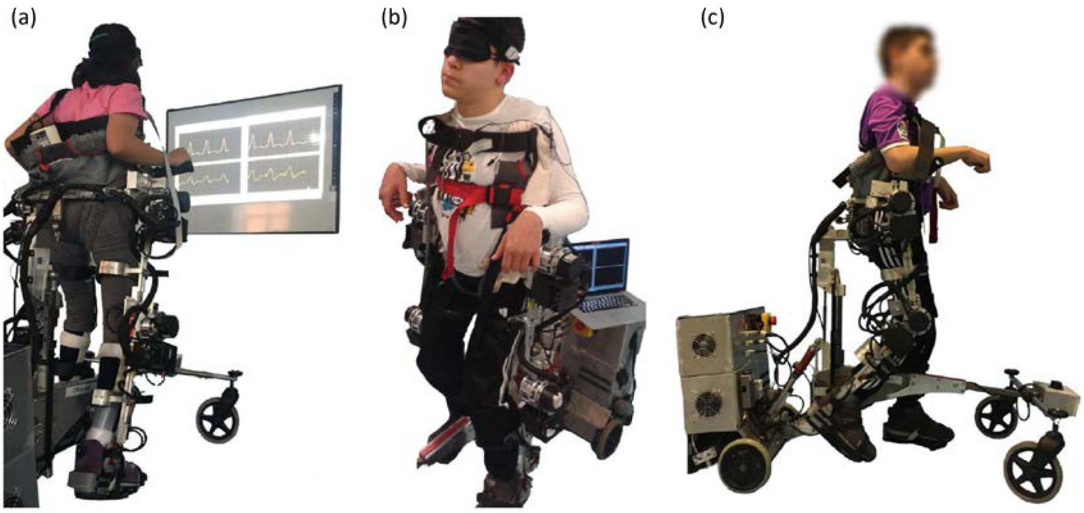


FIGURE 4.5: Representation of several patients working with CPWalker in different session performance: (a) Patient in session 1 of *first phase* (with 100% of PBWS) receiving motion feedback from a screen located in front of her; (b) Patient in session 1 of *first phase* (with 100% of PBWS) wearing a mask on his eyes in order to enhance the motion feeling; and (c) Patient during over-ground walking performing one of the session of the study.

Table 4.3: Levels of assistance in first and second training phases: Position (P); High Impedance (HI); Medium Impedance (MI); Low Impedance (LI). The assistance on knee joint always went behind the assistance on hip, due to the knee movement during gait is performed following inertial forces, assigning to the hip movement higher importance. A higher level is implemented if the session performance (real motion versus desired pattern) is bigger than 85%

	First phase	***Second phase***					
	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Hips	P	HI	MI	MI	MI	LI	LI
Knees	P	P	P	HI	MI	MI	LI

in sessions 9 to 16, position control was substituted by six adapted levels of impedance control in the joints of the exoskeleton (Table 4.3).

One of the main advantages of CPWalker robot was the possibility of selecting three different modes of assistance individualized per joint beyond a pure position control (high, medium and low impedances). In consonance with this, six situations (levels) were adopted following the criteria of our clinical partners in order to define the scales of difficulty in the assistance of knees and hips in the second phase (Table 4.3). Thereby, the patients were considered fit to move to the next level when they achieved a performance higher than 85% in the execution of each session, together with its corresponding parameters (ROM, PBWS and gait velocity) represented by Figure 4.4. This percentage of performance was calculated comparing the real motion executed by the children and the desired gait pattern of each session.

4.1.1.3 Postural control

It was important to ensure that throughout all the sessions, patients maintained a proper posture of head and trunk because it facilitates the performance of any activity of daily living, and improves the social interaction, the participation and communication [88, 96]. In this sense, the proposal uses the biofeedback strategy of CPWalker in order to provide biofeedback to the patients each time that they kept an incorrect position of the body during walking (see section 3.2.3). With this goal, the CPWalker robot used IMUs (Technaid, Spain) to measure the rotation of head and trunk in real-time, and give an acoustic feedback when subjects overcame predefined maximum values selected by clinicians. In response to the acoustic feedback, patients were instructed to correct their position, time at which the acoustic feedback ceased. This strategy was previously proved in chapter 3 with promising results in children with spastic diplegia [13].

4.1.1.4 Motivation and inclusion of challenges

In the field of physical rehabilitation, especially in childhood disability, the F-words (Function, Family, Fitness, Fun, Friends and Future) defined by Dr. Rosenbaum [172] become really important. It is essential to maintain a high patients' motivation because this concept could affect treatment outcomes [173]. To address this issue, author introduced challenges with goals in each session of the robot-based therapy with the aim of having a more engaged user. An example of that is a classification board where the children could follow their progression along the different sessions, and they were rewarded when the goals of each session were correctly fulfilled.

Moreover, with the same objective of enhancing motivation, the data collected with the robotic platform was explained to the patients through graphics so they could feel part of the team, and their interest in the treatment increased.

The patient's motivation was subjectively measured in each session through a scale from 0 to 10 points, with 0 being no motivation and 10 being maximum motivation.

4.1.2 Metrics

In order to objectively measure the patient's evolution and due to the lack of homogeneity among children with CP, it was decided to evaluate the progression of the therapy by comparing each patient to himself, instead of maintaining a control group. Some analyses and evaluation metrics were carried out in different occasions of the study (Table 4.4): during the use of the robot, before the treatment begins (pre), in the middle and after the whole sessions (post).

The 10 mwt [174], thought as a method to evaluate the patients' walking velocity, was assessed for two situations: i) normal comfortable walking speed; and ii) maximum walking speed. The time is measured for the intermediate 6 meters to allow for acceleration and deceleration. Three trials were collected for each situation and subsequently, the average of the three trials was calculated.

Regarding the 6 mwt, it was performed indoors along a flat corridor, where the walking course had a 30 m length and was marked every 3 m [175]. The turnaround points were marked with cones. The patients received information about remaining time every minute, but they were not encouraged during the exercise [176]. The heart rate was also measured for each patient in two situations: resting and just after finishing the test. This parameter gives the possibility of calculating the Physiological Cost Index (PCI) after the exercise, which is used to quantify the energy expended by the patients during the exercise and their progression, [177].

3D gait analysis was recorded at 200 Hz using a motion capture system Smart-DX (BTS Bioengineering, Italy). In order to obtain gait kinetics, a set of reflective markers were placed over the skin on discrete anatomical sites according to the Helen Hayes Model [178]. Subjects walked barefoot at a self-selected speed.

Maximum isometric strength was measured in kgf with a hand-held dynamometer, microFET2 (Hoggan Scientific LLC, USA). Three records were taken and averaged for each movement bilaterally (dorsiflexion, plantarflexion, knee flexion-extension, hip flexion-extension, abduction and adduction).

The particularity of the SCALE assessment [128] was that it was evaluated by the same physiotherapist bilaterally on three occasions (pre, middle and post), with the aim of reducing the subjective error. This metric was used to quantify the patients' capacity to perform selective voluntary motor control.

The changes of GMFM-88 [179] were collected for the 88 items, but the comparison analyses were implemented only for dimensions D (standing) and E (walking).

The kinesiophobia assessment consisted of a test composed of 10 questions of 1 to 4 points each, were queries about fear and pain where evaluated before treatment begins and in a post assessment. The responses were given by the patients without parents influence.

Two FAQ questionnaires were requested [180]: one as initial questionnaire at the beginning, and the other as follow up at the end of the treatment. These surveys presented several questions for parents and others referred to children, which evaluate their expectations, opinion about the therapy, improvements and general feeling.

During the whole treatment, ROM performance and force interactions were measured for each session in order to evaluate if the patient was prepared to jump to the next stage with more difficult parameters and level of assistance.

Finally, the users' motivation was subjectively evaluated by the practitioner from 0 to 10 points for each session with the robot.

Table 4.4: Evaluation metrics and moment of application

Metric	**Utility**	**When**			
		During	Pre	Middle	Post
10-meter walking test (10 mwt) [174]	Gait-speed measure		*	*	*

(To be continued in the next page)

TABLE 4.4: Continuation of Table 4.4

Metric	**Utility**	**When**			
		During	Pre	Middle	Post
6-minutes walking test (6 mwt) [175]	Global responses involved during exercise. Walked distance and endurance		*	*	*
Physiological Cost Index (PCI) [177]	Energy expended			*	*
3D gait analysis	Kinematics, spatial-temporal parameters, gait deviation index (GDI), gait profile score (GPS)...		*	*	*
Maximum isometric strength with hand-held dynamometer	Maximum voluntary contraction of primary lower limbs muscles		*	*	*
Selective Control Assessment of Lower Extremity (SCALE) [128]	Quantify selective voluntary motor control and its progression		*	*	*
Gross Motor Function Measure (GMFM-88) dimensions D (standing) and E (walking) [179]	Evaluate changes in gross motor function according to activities as walking, running or jumping		*		*
Kinesiophobia assessment	Psychological influence of fear and pain		*		*

(To be continued in the next page)

Table 4.4: Continuation of Table 4.4

Metric	**Utility**	**When**			
		During	Pre	Middle	Post
Gillette Functional Assessment Questionnaire (FAQ) [180]	Independent activities, locomotor abilities and user's satisfaction		*		*
ROM performance	Measure of ROM in lower limbs during robot walking	*			
Selective force	Evolution of forces executed by the user during robot walking	*			
Patient's motivation	Estimation of user's motivation in 0 to 10 scale	*			

4.2 Validation with pediatric population

4.2.1 Patients' recruitment

Four children diagnosed with spastic CP affecting muscle strength and motor control of lower limbs (two male, two female, weight 44.75±6.29 kg, height 1.56±0.29 m and age 14.50±2.38 years-old) were selected to be participants for testing the robotic training proposal. The patients of this study are different from those of the preliminary validation presented in point 3.4 of chapter 3, therefore, in order to continue with the numeration, they will be numbered starting from 4 (P4, P5, P6 and P7 in Table 4.5). The inclusion criteria for patients' recruitment in this case followed: i) children aged 11 to 18 years suffering from spastic diplegia; ii) GMFCS levels I to IV; iii) maximum weight 75 kg; iv) anthropometric measures of lower limbs according to the exoskeleton of CPWalker; v) capable of understanding the proposed exercises; and vi) able to signal pain or discomfort. The exclusion criteria was: i) patients who experimented concomitant treatments 3-months prior study (e.g. orthopedic surgery or botulinum toxin); ii) children with muscle-skeletal deformities or unhealed skin lesions in the lower limbs that

TABLE 4.5: Patients' description. Two females (F) and two males (M) with spastic diplegia were selected. No medication 3-months prior the study was taken by the patients. The type of walking support without the aid of the robot is indicated for a distance of 50m and 500m: crutches-CT, wheelchair-WC, posterior walker-PW and cane.

Patient	Age	GMFCS	Weight (kg)	Height (m)	Walking support 50m	Walking support 500m
P4 (F)	12	III	40	1.56	CT	WC
P5 (F)	16	II	42	1.60	Cane	Cane
P6 (M)	17	III	54	1.53	PW	WC
P7 (M)	13	II	43	1.55	-	-

could prevent the use of the exoskeleton; iii) patients with critical alterations of motor control as dystonia, choreoathetosis or ataxia; iv) aggressive or self-harming behaviors; and v) severe cognitive impairment. The study was carried out at "Hospital Infantil Universitario Niño Jesús", (Spain). The Local Ethical Committee of this hospital gave approval to the study (R-0032/12) and warranted its accordance with the Declaration of Helsinki. All participants and families were informed, and parental consents were obtained prior to participation. The study was publicly registered with the number ISRCTN18254257 on March 23, 2017.

4.2.2 Results

Due to reasons unrelated to the study, three of the four patients (P4, P5 and P7) completed 15 of a possible 16 total sessions. Concretely, P4 lost the session number 8, P5 lost the number 7 and P7 the number 11. The rest of training was completed successfully.

The modifications of parameters (ROM, PBWS and gait velocity) proposed in Figure 4.3 and Figure 4.4, were fulfilled by all children without problems. The progressions of the levels of assistance provided by Table 4.3, which were tailored for each patient between sessions 9 to 16 (power training with AAN strategies), are represented in Figure 4.6, where the maximum reached level was level 5 by P4 in the last two sessions.

Figure 4.6: Levels of assistance (L1 to L6) depending on the patient (P4 to P7) and the AAN session (S9 to S16). The patients could jump to the next level if they achieved at least the 85% of the pattern desired for each session. The level for P7 in S11 is not represented because P7 lost this session.

4.2.2.1 Gait speed, endurance and global responses

All patients improved the outcomes in D and E dimensions of the GMFM-88 scale [179] (Figure 4.7 (a)). Results, comparing pre and post studies, show normalized improvements per patient in this scale of 91.58% for P4, 6.31% for P5, 143.52% for P6 and 22.58% for P7 (Figure 4.7 (a))

The SCALE assessment [128], also showed better results at the end of the robot-based treatment (Figure 4.7 (b)). In this case, although the value for the left leg in P4 was kept same as at the beginning (Figure 4.7 (b), red bars for P4), the rest of measures were increased or maintained as maximum (SCALE equal to 10 points).

Finally, both the walked distance in the 6 mwt and the walking speed in the 10 mwt increased after the training period (Figure 4.7 (c) and (d) respectively). The two situations evaluated for the 10 mwt are represented: a comfortable speed for each child (blue bars in Figure 4.7 (d)) and the same exercise at maximum speed (orange bars in Figure 4.7 (d)). More concretely, the percentage of progressions comparing post and pre-analysis in these metrics, were: P4 (6mwt: 26.92%; $10mwt_{comf}$: 94.69%; $10mwt_{max}$: 51.84%); P5 (6mwt: 14.86%; $10mwt_{comf}$: 21.85%; $10mwt_{max}$: 5.18%); P6 (6mwt: 75.68%; $10mwt_{comf}$: 52.21%; $10mwt_{max}$: 24.60%) and P7 (6mwt: 7.27%; $10mwt_{comf}$: 18.60%; $10mwt_{max}$: 0.81%).

The Physiological Cost Index was evaluated comparing middle and post assessments during the 6mwt (see Figure 4.8). All patients reduced the PCI: P4 obtained 0.75 beats/m (middle) and 0.55 beats/m (post); P5 0.89 beats/m (middle) and 0.80 beats/m (post); P6 1.57 beats/m (middle) and 1.26 beats/m (post); and P7 0.33 beats/m (middle) and 0.03 beats/m (post).

Figure 4.7: (a) Results of GMFM-88 (D and E dimensions), (b) SCALE, (c) 6 mwt, and (d) 10 mwt in pre, middle and post analysis for all the patients (P4 to P7). The SCALE was measured bilaterally (left and right). The 10 mwt was performed in two situations: comfortable speed (Comf) and maximum speed (Max).

Figure 4.8: Comparison between middle and post analysis related to the PCI, calculated as a parameter to express the energy cost expended by the patients in the walking distance during the 6 mwt.

Figure 4.9: Maximum strength measures recorded for all the patients in pre (the light-pink line), middle (the dark-pink line) and post analysis (the purple line). Both legs were evaluated, right (R) and left (L).

4.2.2.2 Strength progression

In order to quantify the patient's maximum strength performing on defined and individual movements without the robot, three measures were taken for each required motion. According to that, Figure 4.9 represents the average values (in kgf) of the individualized movements recorded in pre, medium and post analyses. In general, results from Figure 4.9 show that the purple line (post assessment) covers the light-pink line (pre measures) for all the patients. In some cases, it even covers the dark-pink line (measured just after finishing the first 8 strength training sessions). This means that higher values of strength were reached by the children after the robot-based treatment. Concretely, the general improvements (including all the required movements) per patient in maximum isometric strength measure, comparing pre and post averages, were: P4: 129.77±58.71%; P5: 61.39±58.55%; P6: 70.54±83.68% and P7: 34.41±30.41%.

4.2.2.3 Kinematics and spatiotemporal variability

The 3D kinematic analysis provided outcomes focused on gait improvements respect to normality. The GPS and GDI (Figure 4.10) are accepted indexes that represent how close the patient's gait is to the desired gait. Related to these metrics and comparing

FIGURE 4.10: (a) GPS and (b) GDI for pre, middle and post kinematic analyses of patients P4 to P7. The results represent means ± standard error bilaterally (left in red bars and right in green bars). Normality in GPS considers values lower than 7 points (doted-black line in (a)), and normality in GDI comprehends values higher than 100 points (doted-black line in (b)).

pre and post analyses, all the patients obtained better values for both sides (left and right) after the robot-based treatment. Nevertheless, they were not clinically significant, except for the right side of P4 (around 10 points in GDI). It is important to highlight that the post results in P7 could be affected by personal circumstances non-related to the study occurred the day of the test.

Table 4.6 shows the values of Figure 4.10 in detail and also includes some of the spatial-temporal parameters recorded during the studies. The average improvement percentages (four patients) in spatiotemporal parameters were: 21.46±33.79% for mean velocity, 2.84±13.96% for cadence and 17.95±20.45% for step length.

4.2.2.4 ROM performance

Although all the patients succeeded the changes in the parameters of ROM, velocity and PBWS for the different sessions, the progression in AAN levels was individualized for each subject (Figure 4.6). Thereby, P4 was the most advanced, achieving level 5 as the maximum. An example of ROM performance difference between trajectory tracking and AAN strategy is represented by Figure 4.11, which shows the data collected for P4 in

TABLE 4.6: Spatial-temporal parameters, GPS and GDI values for pre, middle and post analyses in all the patients. Results were calculated taking an average of 40 steps

Patient	Analysis	Side	Stride time (s)	Mean velocity (m/s)	Cadence (step/min)	Step length (m)	Gait Profile Score	Gait Deviation Index
	Normality		**0.93±.04**	**1.20±.20**	**129.60±8.40**	**0.58±.06**	**<7**	**>100**
P4	Pre	Left	1.52±.12	0.50±.10	79.05±7.51	0.39±.02	13.80±.50	70.19±1
		Right	1.54±.15			0.38±.04	13.70±.60	73.50±1.13
	Middle	Left	1.81±.04	0.40±0	66.20±1.58	0.25±.18	12.60±.10	73.43±.30
		Right	1.82±.12			0.40±.03	11±.60	79.82±2
	Post	Left	1.27±0	0.80±0	96±1.30	0.46±.04	12.60±.10	75.62±.16
		Right	1.23±.03			0.56±.02	10.50±.40	82.87±1.42
P5	Pre	Left	1.42±.04	0.50±0	86.70±5.19	0.26±.01	20±.60	68.81±1.23
		Right	1.36±.11			0.39±.01	14.90±.30	73.08±.78
	Middle	Left	1.43±.08	0.40±0	86.80±1.86	0.22±.02	19.60±.40	66.93±.84
		Right	1.34±.04			0.39±.01	15.10±.50	72.83±1.41
	Post	Left	1.58±.14	0.40±.10	76±7.50	0.25±.04	18.80±.40	68.12±.87
		Right	1.61±.18			0.41±0	14.80±.40	73.96±1.21
P6	Pre	Left	1.33±.27	0.30±0	84.90±9.90	0.27±.01	15.50±.60	68.23±1.19
		Right	1.58±.03			0.15±.03	13.30±.20	71.67±0.20
	Middle	Left	1.73±.23	0.20±.10	66.20±8.23	0.17±.12	14.80±.80	70.08±1.91
		Right	1.98±.25			0.12±.04	11.70±.70	77.08±2.03
	Post	Left	1.43±.08	0.40±0	86.80±4.45	0.39±.01	14±.20	70.11±.16
		Right	1.35±.08			0.14±.10	12.40±.70	74.46±1.88
P7	Pre	Left	1.02±.06	0.80±0	121.20±7.12	0.41±.03	14.50±.30	71.43±.57
		Right	0.97±.06			0.37±.02	9.90±.30	78.39±.63
	Middle	Left	1±.05	0.90±0	121.35±4.48	0.44±.01	14.20±.60	75.94±1.70
		Right	0.99±.03			0.44±.01	7±.50	90.23±1.42
	Post	Left	0.96±.02	0.90±0	121.20±1.80	0.46±.03	14.40±.80	72.59±2.17
		Right	1.02±.01			0.47±0	9.90±.20	80.13±0.33

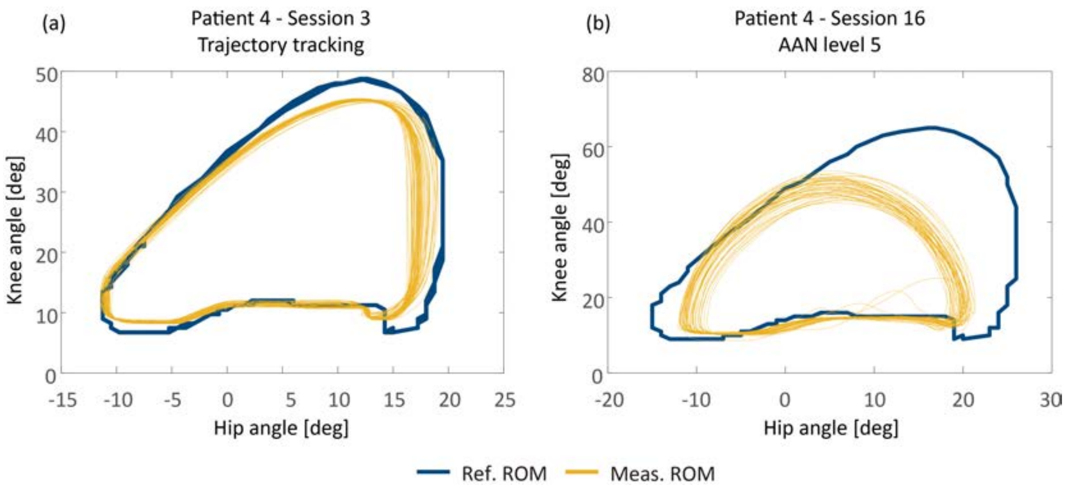


FIGURE 4.11: ROM performance of some steps walking with CPWalker in two situations: (a) Session 3 for patient 4 (*first phase* of the training with trajectory tracking) and (b) Session 16 for patient 4 (*second phase* of the training through AAN strategies with level 5 of assistance (LI at hips and MI at knees)).

session 3 (Figure 4.11 (a)) and session 16 (Figure 4.11 (b)). The last one was recorded within level 5 (low impedance at hips and medium impedance at knees).

4.2.2.5 Qualitative variables

The motivation of each patient was subjectively evaluated by the practitioner who was with the children during the whole period of the study. In each training session, the practitioner assigned a score comprehended in a scale from 0 to 10 points to each child, based on levels of interaction, patient's participation and initiative. The averaged motivation values were: 9.4 for P4, 8.6 for P5, 9.44 for P6 and 8.87 for P7.

Moreover, three of four patients decreased the kinesiophobia score after the 16 sessions. P4 and P6, who were the most affected cases, reduced the score 5 and 6 points respectively, over 40.

4.2.2.6 Patients' judgement

Parents and patients filled a FAQ questionnaire at the beginning and a follow-up at the end of the treatment. Regarding parent questionnaires, results show that all of them thought that the strength and mobility were better at the end of the study thanks to the robot-based therapy. Meanwhile half of them also included the endurance as an improved variable due to the robot. 100% of parents felt satisfied towards the results of robotic therapy with CPWalker, and they ensured that they would like to do it again.

Nevertheless, 75% of them indicated that they had preferred a longer treatment in order to achieve higher changes.

The patients' opinion was very similar. They were also satisfied and, in general, they described the treatment as: "really fun", "the robot makes you feel light and independent" and "safe".

The main limitations founded by patients in CPWalker platform were: i) the harness for the PBWS, which in some occasions was a bit uncomfortable; and ii) the lack of a steering wheel to control the turns.

4.3 Discussion and conclusion

The main aim of this chapter was to provide a first approach to the implementation of a novel and defined robotic rehabilitation method that could cover the most important clinical aspects of the ICF-CY framework. This proposal was tested with four pediatric patients with CP, which provided some preliminary outcomes to assess it. Although the patients' progression was evaluated without a control group, it was not considered as a relevant limitation of the study, since the wide variety of differences among each child with CP makes interesting and even necessary to expose the improvements by comparing each patient with himself.

According to the results, the greatest benefits due to the robot-based treatment corresponded to P4 and P6, who were the most affected levels of GMFCS (III in both cases). In general, the higher values of gait speed and improved values of global responses achieved by all the children in several tests, may be in benefit of the patients' social mobility. Visual inspection of the graphics show that changes appeared after a small number of sessions (middle tests) and they were commonly increased or maintained until the post studies.

The most challenging part was the second phase of the training, which allowed the possibility of adapting the level of assistance depending on the patient's progression. Thereby, any subject could achieve the last level (level 6), and although the action of reaching level 4 took P6 longer than the rest of children, this patient could pass through it in the last three sessions.

It is interesting to highlight that the outcomes from isometric strength measure showed important peaks of improvement, especially for hip and knee flexion-extension, which was targeted with the CPWalker robotic platform. These higher values were observed from the middle to the post analysis. The results of the present study are difficult to compare with the scientific literature due to the lack of studies using exoskeletons for gait resistance training. However, the presented results are in line with previous studies assessing conventional resistance strength training in CP [181].

In relation to 3D-kinematic analysis, as it was said before, P7 suffered a non-grata personal situation the day of the post study. We believe this affected the results of this metric. Nevertheless, the whole population improved the values for spatiotemporal parameters, GDI and GPS, although some of these improvements were not clinically significant. It is important to highlight that not only the kinematics was improved, also the physiological expenditure in walking activities decreased, as illustrated by the reduction of the PCI in all patients, which means that better gait performance implies lower energy cost.

Finally, the motivation scale for the patients and the parents' satisfaction with the robot-based treatment was very high in most aspects.

The greatest achievements of this proposal come from the possibility of exercising different gait functions in an orderly way, individualized per joint and at the same time than over-ground walking. The proposed protocol could be applied to any current robotic device for gait rehabilitation making minimal changes on it: e.g. in treadmill pediatric platforms as Lokomat [182], despite the impossibility of over-ground walking, it already has different controllers, whose operation modes are close to the levels of impedance of CPWalker, ensuring the progression of the therapy into the sessions. Regarding working postural control in parallel with lower limbs training, which we considered one of the key factors of the study, it may be solved through other solutions if the selected robotic device does not have a similar strategy as described with CPWalker, but it is crucial to guarantee its compliance to get the best results of the treatment [88].

The principal limitation of this research is that it was followed up only in short-term, so further research with a higher population size is needed to evaluate if the improvements will be kept over time. Moreover, although other studies propose interventions on 3 non-consecutive days per week [181], the patients of the present study performed the robotic exercises during 2 non-consecutive sessions per week. This enabled them to continue their conventional therapies in parallel to the robot-based rehabilitation. The conventional therapies had been attended on a regular basis for years, so authors considered to not abolish them for ethical reasons. The conventional therapies of the patients were performed 2 days a week and consisted of exercises on balance and strength focusing on quadriceps and abs. Although the patients were doing conventional and robotic therapy in parallel, authors consider that the improvements achieved in this proposal are exclusively associated to the use of the CPWalker, since the patients got non-robotic therapies for years with no significant improvements. In conclusion, the method implemented with

CPWalker is complementary to the common therapies, providing new possibilities to the clinical practice through robotic rehabilitation and also reaching better outcomes than conventional therapy alone.

In a nutshell, this chapter contributed with a defined robotic treatment that could be implemented in most of the existing rehabilitation robotic devices for lower limbs, and which was evaluated positively in four patients with CP using CPWalker.

Chapter 5

Conclusion and Future Directions

This final chapter presents the most important contributions and main conclusions of this dissertation, enhancing their significance. Likewise, the chapter also includes approaches for future work and exposes some of the principal publications derived from the thesis as an index of its scientific quality.

5.1 Contributions

This doctoral thesis has been developed with the main aim of providing a new robotic solution to improve gait rehabilitation of children with CP and other patients with related disorders. In order to achieve this objective, author established a work methodology, which came from an extended review of the state-of-the-art for robotic rehabilitation in different pathologies, apart from the bibliography destined to young people with CP. In this review, several gaps were identified for the current therapies and rehabilitation devices, being the beginning for the development of this dissertation:

- The need of improving conventional non-robotic therapies due to the lack of effectiveness and movement accuracy. Therapists' limitation is the main cause of this shortcoming, and it is also reflected in the scarce duration of the therapy.
- The absence of versatility and adaptability of the current robotic therapies and devices to the different patients' needs.
- The necessity of robotic devices that may execute rehabilitation exercises not only focusing on peripheral structures, but also including CNS.

- The lack of gait trainings that motivate the patients through task specific exercises, using control strategies that require patients' collaboration to perform the movements.
- The absence of robot-based gait therapies that incorporate postural control as a main part of recovery during walking, executing different gait functions in parallel.
- The lack of studies that provide defined guidelines about the implementation of robotic therapies in the existing rehabilitation devices.

This dissertation tried to cover all the exhibited limitations. The main contributions of the thesis are summarized in the next points:

- Exposition of a general and descriptive review of the common therapies implemented in CP and the state-of-the-art in robot-based rehabilitation, comprising robotic devices for both upper and lower limbs. This review helped to perceive the main advantages and disadvantages of both non-robotic therapies and current robotic platform for gait rehabilitation in CP (chapter 1).
- Identification of users' needs in order to establish the design criteria for a new robotic device that covered previous requirements, complementing the advantages of current robotic devices with novel solutions to improve the rehabilitation (chapter 2).
- Developing of a robotic platform (CPWalker) for gait rehabilitation of children with CP. This encompassed mechanical structure and control architecture of the device (chapter 2).
- Analysis, definition and technical evaluation of several control strategies for gait rehabilitation in CPWalker platform. Different algorithms were proposed, whose combination in several ways provided novel tailored treatments depending on the rehabilitation stage of each patient (chapter 3).
- Presentation of a clinician interface to control the robotic platform accordingly. It allowed quick and intuitive definition of exercises, as well as the assessment of patients' progression within the robotic treatment (chapter 3).
- Preliminary evaluation of CPWalker robotic platform in three children with spastic diplegia. The outcomes obtained in this phase offered promising prospects to use the device into clinical environments (chapter 3).
- Transfer to other robotic devices the novel concepts and control strategies initially developed for CPWalker. Particularly, the performance-based adaptive controller opened new horizons in the research with LOPES II gait trainer (chapter 3).

- Description and evaluation of a defined therapy protocol for gait rehabilitation of four children with CP. The study provided notable advances for all children in short-term, and it contributed with better answers on how to use robot-based rehabilitation in a orderly way (chapter 4).

- Technological transfer of this project to other research centres as RIC with the aim of starting a collaboration for future studies with CPWalker platform (chapter 5).

5.2 CPWalker in perspective and future work

5.2.1 CPWalker in perspective

Throughout this doctoral thesis, the author reviewed existing robotic devices for the rehabilitation of children with neurological disorders. Chapters 1 and 2 presented a comparison between the main gait trainers, exposing their principal advantages, but also the expected challenges to improve traditional rehabilitation. This section intends to provide a new perspective of CPWalker to better know where is its real position comparing to the rest of robotic rehabilitation devices. In [183], Meuleman contrasted the recommended use of LOPES II gait trainer with the training coverage according to the patients' Functional Ambulation Category (FAC). FAC [184] is a functional walking scale that evaluates patients' ambulation ability by 6 levels (from 0 to 5). It is mainly used with, but not limited to, patients with stroke. In order to replicate this comparison with CPWalker robotic platform, Figure 5.1 shows the suitability of several types of RAGT as a function of FAC.

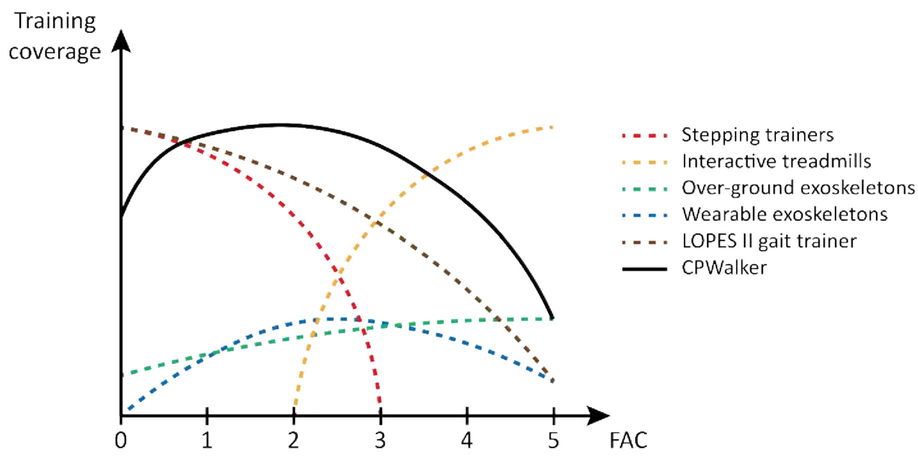


FIGURE 5.1: Recommended use (training coverage) of CPWalker and other RAGT as a function of FAC.

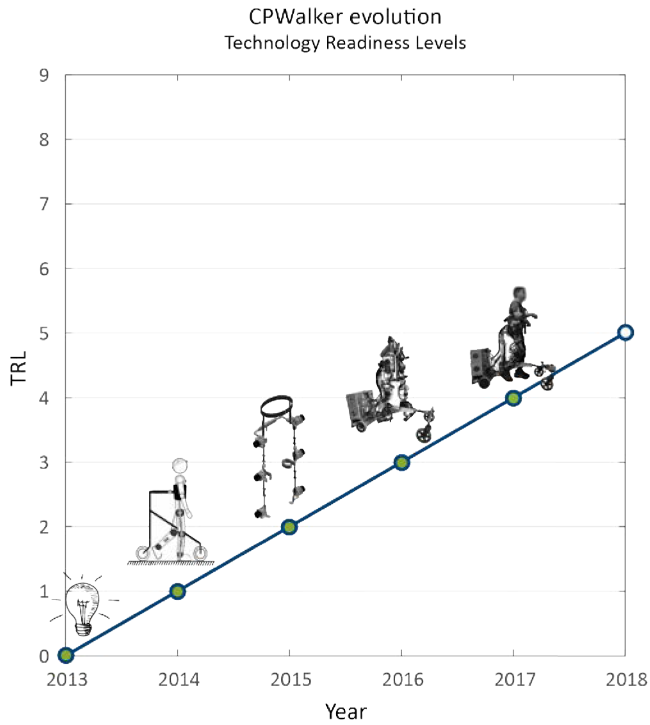


Figure 5.2: Progression of CPWalker in the last years as a function of TRL.

To assess the actual maturity level of CPWalker and its evolution since the beginning of the project, the Technology Readiness Level (TRL) scale has been used. In this regard, Figure 5.2 presents how was the progression of CPWalker development from year 2013 to the present. Author expects that the robotic platform may reach a TRL 5 at the end of 2018.

5.2.2 Future work

The work developed in the framework of this thesis and the obtained results, open future research lines. Some of them are studies that were ruled out from the dissertation due to time-restrictions, and others are new projections derived from questions that appeared during the elaboration of the thesis and results analysis.

5.2.2.1 Improvement of mechanical design

The mechanical design of CPWalker should be improved in different ways, but the most important part that the author considers is to increase the number of DOFs in order to improve the kinematic compatibility of CPWalker with the user. The more DOFs the more transparency of the exoskeleton to the subject. This includes both actuate and/or provide free motion to DOFs that are currently constrained. In this regard, pelvis motion is really influential in gait function, and therefore the author considers a priority to provide freedom for pelvis transversal rotation and pelvis frontal rotation.

Moreover, it would be desirable to reduce the complexity of the mechanical assembly for each actuated joint of CPWalker. The current design is composed by too many pieces that make really difficult to maintain the alignment after the fabrication process. Both new and existing DOFs for joints should be assembled easily for a better system operation and eradication of possible misalignments.

5.2.2.2 Improvement of human-robot interaction

The improvement of human-robot interaction would result in an enrichment of robotic therapies because it implies more patient's active participation through CNS. An idea to do that could be the utilization of EEG not only as a trigger to start the movement, but also to detect patient's intention to make turns, stop the robot or go faster. In this regard, other technologies as electromyography (EMG) could be also used to detect intention of movement or to control the gait. The author also considers EMG measurement as a good estimator for the assessment of patient's progression. It would be interesting to integrate EMG in future treatments with CPWalker.

5.2.2.3 Definition of novel treatment protocols

"Contrary to our initial expectations, the major hindrance to the development and deployment of robots for therapy was not engineering, but the lack of strong evidence supporting many current rehabilitation practices." (Krebs and Hogan, 2006).

RAGT needs to be innovative and defined with goal-directed task. Robotic devices provide objective measurement and control of the exercise, but new research to validate the effectiveness and usability of RAGT to complement traditional therapies is needed. Some author's assumptions to improve robotic therapies are:

- The combination of functional electrical stimulation (FES) with intensive robotic gait training is expected to boost the rehabilitation of children with CP by optimizing cortex activation and generating neural changes. The effects of FES with locomotor training have been satisfactorily proven in individuals with Spinal Cord Injury [185], but studies are scarce in pediatric population with CP.

- Activities of daily living require simultaneous tasks. To promote the patient a sense of body-ownership, the effect of dual-task conditions should be evaluated meanwhile robotic over-ground walking is performed.

- Backward walking appeared as an emerging rehabilitation approach to enrich the traditional physical therapies of forward walking [186–188]. Benefits of backward walking are classified as: i) neurological; ii) cardiovascular; and iii) gait responses in forward walking. Although backward walking has been proven in traditional physical therapy, no studies have been found in robotic rehabilitation.

5.2.2.4 Robotics as assessment

A proposed method for assessing the walking function could be the robotic assistance required by a patient to perform the different subtasks of gait [43]. An adaptive algorithm developed in the framework of this dissertation (see sections 3.2.2 and 3.5) can automatically adjust the assistance provided by the robotic platform based on patient's performance. The study of how the robotic assistance progresses along therapy sessions could be an important aspect to assess the patient's evolution into the robotic treatment.

5.2.2.5 Maximise impact

A possible limitation of this thesis is that robotic studies with CPWalker were evaluated with a short population size. Future research should involve larger number of patients to definitively validate the proposed algorithms and training procedures. Following this purpose, a new CPWalker platform was assembled last year, and it is being tested at Shirley & Ryan Ability Lab (former RIC) with 70 patients since February 2018 in order to develop new robotic treatments with a larger population with CP.

5.3 Scientific dissemination

5.3.1 Publications

This thesis, focused on the development and evaluation of CPWalker rehabilitation platform, has allowed the author to work into several robotics fields. This fact is reflected by the generated scientific contributions, which represent an indicator of the quality collected in this book. Points below show the main generated publications depending on the type of dissemination.

5.3.1.1 Journal articles

- C. Bayón, S. Lerma, O. Ramírez, J.I. Serrano, M.D. Del Castillo, R. Raya, J.M. Belda-Lois, I. Martínez, E. Rocon, *Locomotor training through a novel robotic* *platform for gait rehabilitation in pediatric population: short report*, Journal of NeuroEngineering and Rehabilitation, 10.1186/s12984-016-0206-x, 13:98, 2016.

- C. Bayón, T. Martín-Lorenzo, B. Moral-Saiz, O. Ramírez, A. Pérez-Somarriba, S. Lerma, I. Martínez, E. Rocon, *A robot-based gait training therapy for pediatric population with Cerebral Palsy: goal setting, proposal and preliminary clinical implementation*, Journal of NeuroEngineering and Rehabilitation, under review, 2018.

- C. Bayón, O. Ramírez, J.I. Serrano, M.D. del Castillo, A Pérez-Somarriba, J.M. Belda-Lois, I. Martínez, S. Lerma, C. Cifuentes, A. Frizera, E. Rocon, *Development and evaluation of a novel robotic platform for gait rehabilitation in patients with Cerebral Palsy: CPWalker*, Robotics and Autonomous Systems, 10.1016/j.robot.-2016.12.015, 91:101-114, 2017.

- C. Bayón, R. Raya, S. Lerma, O. Ramírez, J.I. Serrano, E. Rocon, *Robotic Therapies for Children with Cerebral Palsy: a systematic review*, Translational Biomedicine, 10.21767/2172-0479.100044, 7-1:14, 2016.

- C. Cifuentes, L.F. Aycardi, M. Munera, C. Bayón, O. Ramírez, E. Rocon, A. Frizera, S. Lerma, *Evaluation of biomechanical gait parameters of patients with Cerebral Palsy at three different levels of gait assistance using CPWalker*, Journal of NeuroEngineering and Rehabilitation, under review, 2018.

- S. Lerma, I. Martínez, C. Bayón, M.D. del Castillo, I. Serrano, R. Raya, J.M. Belda, T. Martín, B. Moral, A. Barragán, E. Parra, M. Loma-Ossorio, A. Pérez, E. Rocon, *Can robotic-based top-down rehabilitation therapies improve motor control in children with cerebral palsy? A perspective on the CPWalker project*, Biomedical Research and Clinical Practice, 10.15761/BRCP.1000106, 1:1, 2016.

5.3.1.2 Conference proceedings

- C. Bayón, O. Ramírez, M.D. del Castillo, J.I. Serrano, R. Raya, J.M. Belda, R. Poveda, F. Mollà, T. Martín-Lorenzo, I. Martínez, S. Lerma, E. Rocon, *CPWalker: Robotic platform for gait rehabilitation in patients with Cerebral Palsy*, IEEE International Conference on Robotics and Automation (ICRA), 2016.

- C. Bayón, O. Ramírez, M.Velasco, J.I. Serrano, S. Lerma, I. Martínez, E. Rocon, *Pilot Study of a Novel Robotic Platform for Gait Rehabilitation in Children with Cerebral Palsy*, 6th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), 2016.

- C. Bayón, S.S. Fricke, E. Rocon, H. van der Kooij, E.H.V. van Asseldonk, *Performance-Based Adaptive Assistance for Diverse Subtasks of Walking in a Robotic Gait Trainer: Description of a New Controller and Preliminary Results*, EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), under review, 2018.

- C. Bayón, T. Martín-Lorenzo, O. Ramírez, B. Moral-Saiz, A. Pérez-Somarriba, S. Lerma, I. Martínez, E. Rocon, *Proposal of a robotic therapy for pediatric population with Cerebral Palsy*, Annual Symposium of the IEEE EMBS Benelux Chapter, 2017.

- C. Bayón, S.S. Fricke, E. Rocon, H. van der Kooij, E.H.V. van Asseldonk, *Performance-based adaptive assistance for different subtasks of walking in LOPES II*, Annual Symposium of the IEEE EMBS Benelux Chapter, 2017.

- C. Bayón, S. Lerma, O. Ramírez, J.I. Serrano, M.D. del Castillo, J.M. Belda, R. Raya, E. Rocon, *Gait Rehabilitation in Pediatric Population through a Novel Robotic Platform: Pilot Study*, XXI International Society of Electrophysiology and Kinesiology (ISEK), Student award winner, 2016.

- C. Cifuentes, C. Bayón, S. Lerma, A. Frizera, E. Rocon, *Pilot Study of a Novel Robotic Platform for Gait Rehabilitation in Children with Cerebral Palsy*, 6th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), 2016.

- C. Bayón, T. Martín-Lorenzo, O. Ramírez, B. Moral-Saiz, A. Pérez Somarriba, S. Lerma-Lara, I. Martínez, E. Rocon, *Entrenamiento robótico de la marcha en pacientes con Parálisis Cerebral: definición de objetivos, propuesta de tratamiento e implementación clínica preliminar*, XXXVIII Jornadas de Automática, 2017.

- C. Bayón, S. Lerma, O. Ramírez, J.I. Serrano, M.D. del Castillo, J.M. Belda, I. Martínez, E. Rocon, *Gait Rehabilitation in Pediatric Population through CP-Walker Robotic Platform*, XXXVII Jornadas de Automática, 2016.

- C. Bayón, C. Cifuentes, O. Ramírez, R. Raya, M. Velasco, A. Frizera, E. Rocon, *CPWalker. Interacción humano-robot basada en sensor láser para rehabilitación de la marcha de niños con parálisis cerebral*, VIII Congreso Iberoamericano de Tecnologías de Apoyo a la Discapacidad (Iberdiscap), 2015.

- C. Bayón, E. Rocon, R. Raya, O. Ramírez, M.D. del Castillo, J.I. Serrano, S. Lerma, *CPWalker: plataforma robótica para la rehabilitación de la marcha en niños con Parálisis Cerebral*, VI Congreso Internacional de Diseño, Redes de Investigación y Tecnología para todos (DRT4all), Best paper award, 2015.

- C. Cifuentes, L.F. Aycardi, M. Munera, C. Bayón, O. Ramírez, E. Rocon, A. Frizera, S. Lerma, *Biomechanical comparison of patients with CP with different levels of gait assistance using CPWalker*, 20th International Conference on Climbing and Walking Robots and Support Technologies for Mobile Machines (CLAWAR), 2017.

- J.I. Serrano, M.D. del Castillo, R. Raya, C. Bayón, E. Rocon, I. Martínez, S. Lerma, *BCI basado en la facilitación asociativa de la actividad cortical para el inicio de la marcha en Parálisis Cerebral*, 7º Simposio CEA de Bioingeniería, 2015.

5.3.1.3 Book chapters

- J.I. Serrano, M.D. del Castillo, C. Bayón, O. Ramírez, S. Lerma, I. Martínez, E. Rocon, *BCI-based Facilitation of Cortical Activity Associated to Gait Onset after Single Event Multi-Level Surgery in Cerebral Palsy*, Brain-Computer Interface Research: A State-of-the-Art, Springer, 5:99-110, 2017.

- C. Cifuentes, C. Bayón, S. Lerma, A. Frizera, L. Rodríguez, E. Rocon, *Wearable Robotic Walker for Gait Rehabilitation and Assistance in Patients with Cerebral Palsy*, Covering Clinical and Engineering Research on Neurorehabilitation II, Springer, 1451-1455, 2017.

- T. Martín, S. Lerma, C. Bayón, O. Ramírez, E. Rocon, *CPWalker for Strength Training in Children with Spastic Cerebral Palsy: a training program proposal*, Covering Clinical and Engineering Research on Neurorehabilitation II, Springer, 1211-1215, 2017.

5.3.1.4 Other dissemination activities

- C. Bayón, S. Lerma Lara, O. Ramírez, J.I. Serrano, B. Moral, E. Parra, A. Pérez, J.M. Belda-Lois, I. Martínez, E. Rocon, *Gait Rehabilitation in Pediatric Population through CPWalker Robotic Platform: Pilot Study*, MRS Training day Northwestern University, 2016.

- C. Bayón, *Research Lines of group of Neural and Cognitive Engineering: Novel Robotic Platform for Gait Rehabilitation and Training in Children with Cerebral Palsy*, RIC Research Seminars, 2016.

- Supervision of graduation project: *Desarrollo de un Sistema de Reproducción del Movimiento en Tiempo Real para el Robot Rehabilitador CPWalker*, María Begoña Rojas López, Universidad Politécnica Madrid, 2016.

- C. Bayón, O. Ramírez, *CPWalker: Plataforma robótica para la rehabilitación y el entrenamiento de la marcha en pacientes con Parálisis Cerebral*, RoboRave Ibérica, Fundación Primera Fila, 2016.
- C. Bayón, E. Rocon, *CPWalker: plataforma robótica para la rehabilitación y el entrenamiento de la marcha en pacientes con parálisis cerebral*, 40 Aniversario Escuela de Ingenierías Industriales Badajoz, 2016.
- Award I+D+i "Dependencia y Sociedad" Fundación CASER, CASER, 2017.
- C. Bayón, O. Ramírez, E. Rocon, *CPWalker: plataforma robótica para rehabilitación de la marcha en pacientes con Parálisis Cerebral*, Noche Europea de los Investigadores, 2015.
- C. Bayón, O. Ramírez, E. Rocon, *Tecnología Biónica en medicina: demostración plataforma CPWalker*, Universidad CEU San Pablo, 2015.
- C. Bayón, O. Ramírez, E. Rocon, *Utilización del exoesqueleto CPWalker en la rehabilitación de niños con parálisis cerebral*, Universidad Francisco de Vitoria, 2014.
- Broadcast Órbita Laika TV program, TVE2, 2015.
- Broadcast Madrid Contigo, TeleMadrid, 2017.
- Broadcast "Punto de encuentro", Canal Orbe21 Movistar+, 2017.
- Broadcast Antena3 News, *Ejemplos de campañas solidarias que salvan vidas*, Antena3, 2016.
- Broadcast Cuatro TV, *La carrera de la vida*, Cuatro TV, 2016.
- Broadcast TVE1 News, *Carrera Corre por el Niño*, TVE1, 2016.
- Broadcast TeleMadrid News, *Carrera Corre por el Niño*, TeleMadrid, 2016.
- Broadcast TVE1 News, TVE1, 2015.
- Broadcast TeleMadrid News, TeleMadrid, 2015.
- Radio show news, *Una carrera con exoesqueleto*, COPE, 2016.
- Radio show "El Sol sale por el Oeste", Canal Extremadura, 2016.
- Radio show Mediodía COPE, *El exoesqueleto que permitirá andar a niños con PC*, COPE, 2017.
- CPWalker facilita la rehabilitación de niños con PC, newspaper Tecnobility, 2017.

- El ”levántate y anda” del niño Jesús, newspaper El Mundo, 2015.
- Badajoz acoge una presentación de estudios sobre Parkinson y Parálisis cerebral, journal GRADA, Fundación Primera Fila, 2016.
- La UEx señala que el futuro de la rehabilitación para ictus o apoplegías pasa por utilizar nuevas técnicas robóticas, newspaper EuropaPress Extremadura, 2016.

5.3.2 International experience

During this doctoral thesis, the author carried out two research visits awarded by the Spanish Ministry of Economy and Competitiveness. These research fellowships served to facilitate the transfer of knowledge between the involved centres. It is important to highlight that the first research visit concluded with an important collaboration between Spanish National Research Council and Rehabilitation Institute of Chicago, in which the American centre funded a new CPWalker platform with the aim of testing this robot in United States.

- Research fellowship awarded by Spanish Ministry of Economy and Competitiveness, EEBB-I-16-10663, Rehabilitation Institute of Chicago (United States), from May 22 to September 28, 2016.
- Research fellowship awarded by Spanish Ministry of Economy and Competitiveness, EEBB-I-17-12035, University of Twente (The Netherlands), from September 22 to December 22, 2017.

Bibliography

[1] M. Oskoui, F. Coutinho, J. Dykeman, N. Jetté, and T. Pringsheim, "An update on the prevalence of cerebral palsy: a systematic review and meta-analysis.," *Developmental medicine and child neurology*, vol. 55, pp. 509–19, jun 2013.

[2] K. Van Naarden Braun, N. Doernberg, L. Schieve, D. Christensen, A. Goodman, and M. Yeargin-Allsopp, "Birth Prevalence of Cerebral Palsy: A Population-Based Study.," *Pediatrics*, vol. 137, pp. peds.2015–2872, jan 2016.

[3] C. Bayón, R. Raya, S. L. Lara, Ó. Ramírez, J. Serrano, and E. Rocon, "Robotic Therapies for Children with Cerebral Palsy: A Systematic Review," *Translational Biomedicine*, vol. 7, no. 1, pp. 1–10, 2016.

[4] M. McGinley, F. Dobson, R. Ganeshalingam, B. Shores, E. Rutz, and H. Graham, "Single-event multilevel surgery for children with cerebral palsy: a systematic review," *Developmental medicine and child neurology*, vol. 54, no. 2, pp. 117–128, 2011.

[5] H. I. Krebs, B. Ladenheim, C. Hippolyte, L. Monterroso, and J. Mast, "Robot-assisted task-specific training in cerebral palsy.," *Developmental medicine and child neurology*, vol. 51 Suppl 4, pp. 140–5, oct 2009.

[6] A. Meyer-Heim and H. J. a. van Hedel, "Robot-assisted and computer-enhanced therapies for children with cerebral palsy: current state and clinical implementation.," *Seminars in pediatric neurology*, vol. 20, pp. 139–45, jun 2013.

[7] J. Cao, S. Q. Xie, R. Das, and G. L. Zhu, "Control strategies for effective robot assisted gait rehabilitation: The state of art and future prospects," *Medical Engineering and Physics*, vol. 36, no. 12, pp. 1555–1566, 2014.

[8] S. Lefmann, R. Russo, and S. Hillier, "The effectiveness of robotic-assisted gait training for paediatric gait disorders: systematic review.," *Journal of neuroengineering and rehabilitation*, vol. 14, no. 1, p. 1, 2017.

[9] A. Pascual-Leone, A. Amedi, F. Fregni, and L. B. Merabet, "The Plastic Human Brain Cortex," *Annual Review of Neuroscience*, vol. 28, no. 1, pp. 377–401, 2005.

[10] A. R. C. Donati, S. Shokur, E. Morya, D. S. F. Campos, R. C. Moioli, C. M. Gitti, P. B. Augusto, S. Tripodi, C. G. Pires, G. A. Pereira, F. L. Brasil, S. Gallo, A. A. Lin, A. K. Takigami, M. A. Aratanha, S. Joshi, H. Bleuler, G. Cheng, A. Rudolph, and M. A. L. Nicolelis, "Long-Term Training with a Brain-Machine Interface-Based Gait Protocol Induces Partial Neurological Recovery in Paraplegic Patients," *Scientific Reports*, vol. 6, no. April, 2016.

[11] S. C. Cramer, M. Sur, B. H. Dobkin, C. O'Brien, T. D. Sanger, J. Q. Trojanowski, J. M. Rumsey, R. Hicks, J. Cameron, D. Chen, W. G. Chen, L. G. Cohen, C. Decharms, C. J. Duffy, G. F. Eden, E. E. Fetz, R. Filart, M. Freund, S. J. Grant, S. Haber, P. W. Kalivas, B. Kolb, A. F. Kramer, M. Lynch, H. S. Mayberg, P. S. McQuillen, R. Nitkin, A. Pascual-Leone, P. Reuter-Lorenz, N. Schiff, A. Sharma, L. Shekim, M. Stryker, E. V. Sullivan, and S. Vinogradov, "Harnessing neuroplasticity for clinical applications," *Brain*, vol. 134, no. 6, pp. 1591–1609, 2011.

[12] C. Bayón, O. Ramírez, J. Serrano, M. D. Castillo, A. Pérez-Somarriba, J. Belda-Lois, I. Martínez-Caballero, S. Lerma-Lara, C. Cifuentes, A. Frizera, and E. Rocon, "Development and evaluation of a novel robotic platform for gait rehabilitation in patients with Cerebral Palsy: CPWalker," *Robotics and Autonomous Systems*, vol. 91, pp. 101–114, 2017.

[13] C. Bayón, S. Lerma, O. Ramírez, J. Serrano, M. Del Castillo, R. Raya, J. Belda-Lois, I. Martínez, and E. Rocon, "Locomotor training through a novel robotic platform for gait rehabilitation in pediatric population: short report," *Journal of NeuroEngineering and Rehabilitation*, vol. 13, no. 1, p. 98, 2016.

[14] C. Bayón, T. Martin-Lorenzo, B. Moral-Saiz, Ó. Ramirez, A. Perez-Somarriba, S. Lerma-Lara, I. Martinez-Caballero, and E. Rocon, "A robot-based gait training therapy for pediatric population with Cerebral Palsy: goal setting, proposal and preliminary clinical implementation," *bioRxiv (submitted to JNER)*, p. 255448, jan 2018.

[15] C. Morgan, J. Darrah, A. M. Gordon, R. Harbourne, A. Spittle, R. Johnson, and L. Fetters, "Effectiveness of motor interventions in infants with cerebral palsy: a systematic review," *Developmental Medicine and Child Neurology*, vol. 58, no. 9, pp. 900–909, 2016.

[16] World Health Organization, *International Classification of Functioning, Disability and Health, children and youth version.* World Health Organization, 2007.

[17] M. Bax, D. M. Frcp, P. Rosenbaum, B. Dan, H. Universitaire, R. Fabiola, U. L. D. Bruxelles, M. Goldstein, and D. D. Pt, "Review Proposed definition and classification of cerebral palsy , April 2005 Executive Committee for the Definition of Cerebral Palsy," *Developmental medicine and child neurology*, no. April, pp. 571–576, 2005.

[18] K. L. de Gooijer-van de Groep, E. de Vlugt, J. H. de Groot, H. C. M. van der Heijden-Maessen, D. H. M. Wielheesen, R. M. S. van Wijlen-Hempel, J. H. Arendzen, and C. G. M. Meskers, "Differentiation between non-neural and neural contributors to ankle joint stiffness in cerebral palsy.," *Journal of neuroengineering and rehabilitation*, vol. 10, no. 1, p. 81, 2013.

[19] I. Novak, "Evidence-Based Diagnosis, Health Care, and Rehabilitation for Children With Cerebral Palsy.," *Journal of child neurology*, jun 2014.

[20] S. Winter, A. Autry, C. Boyle, and M. Yeargin-Allsopp, "Trends in the prevalence of cerebral palsy in a population-based study.," *Pediatrics*, vol. 110, pp. 1220–5, dec 2002.

[21] A. Johnson, "Prevalence and characteristics of children with cerebral palsy in Europe.," *Developmental medicine and child neurology*, vol. 44, pp. 633–40, sep 2002.

[22] C. f. D. C. (CDC) and Prevention, "Economic costs associated with mental retardation, cerebral palsy, hearing loss, and vision impairment–United States, 2003.," *MMWR. Morbidity and mortality weekly report*, vol. 53, pp. 57–9, jan 2004.

[23] A. Confederación Española de Federaciones y Asociaciones de Atención a Personas con Parálisis Cerebral y Afines, "Tipos de Parálisis cerebral - Confederación Aspace."

[24] C. Cans, "Surveillance of cerebral palsy in Europe: a collaboration of cerebral palsy surveys and registers. Surveillance of Cerebral Palsy in Europe (SCPE).," *Developmental medicine and child neurology*, vol. 42, no. 12, pp. 816–824, 2000.

[25] R. Palisano, P. Rosenbaum, S. Walter, D. Russell, E. Wood, and B. Galuppi, "Gross Motor Function Classification System," *Developmental Medicine & Child Neurology*, vol. 39, pp. 214–223, 1997.

[26] H. K. Graham, A. Harvey, J. Rodda, G. R. Nattrass, and M. Pirpiris, "The Functional Mobility Scale (FMS).," *Journal of pediatric orthopedics*, vol. 24, no. 5, pp. 514–20, 2004.

[27] S. Rethlefsen, D. Ryan, and R. Kay, "Classification Systems in Cerebral Palsy," *Orthopedic Clinics of North America*, vol. 41, pp. 457–67, 2010.

[28] S. Shonkoff, J. , Meisels, *Handbook of Early Childhood Intervention.* Cambridge University Press, second edn ed., 2000.

[29] H. Anttila, I. Autti-Rämö, J. Suoranta, M. Mäkelä, and A. Malmivaara, "Effectiveness of physical therapy interventions for children with cerebral palsy: A systematic review," *BMC Pediatrics2*, vol. 8, no. 14, pp. 1–10, 2008.

[30] H. Kerr Graham, K. Roger Aoki, I. Autti-Ramo, R. N. Boyd, M. R. Delgado, D. JGaebler-Spira, M. E. GormleyJr, B. M. Guyer, F. Heinen, A. F. Holton, D. Matthews, G. Molenaers, F. Motta, P. Garcia Ruiz, and J. Wisselo, "Recommendations for the use of botulinum toxin type A in the management of cerebral palsy," *Gait & Posture*, vol. 11, pp. 67–79, feb 2000.

[31] L. M. Knutson and D. E. Clark, "Orthotic devices for ambulation in children with cerebral palsy and myelomeningocele.," *Physical therapy*, vol. 71, no. 12, pp. 947–960, 1991.

[32] J. Abad Lara, J. Duart Clemente, M. Aguirre Canyadell, O. Espinazo Arce, A. Albero Sarrió, P. Ferrand-Ferri, L. Antón Rodrigálvarez, J. del Fresno Molina, J. Burgos Flores, I. de Gálvez Aranda, L. Corominas Francés, A. García García, P. Doménech Fernández, S. García Mata, P. Gozález Herranz, T. Martín Lorenzo, P. Jiménez Espuch, L. Ortiz San Román, J. Knörr Giménez, D. Pacha Vicente, S. Lerma Lara, E. Parra Mussín, I. Martínez Caballero, H. Peña Arantzibia, L. Peña Baranda, R. Martino Alba, C. Pérez Díaz, A. Mascarell Gregori, A. Pérez-Somarriba Moreno, J. Monasterio Vicente, A. Presedo Rodríguez, B. Moral Saiz, E. Puchol Castillo, V. Puertas Martín, F. Soldado Carrera, A. Ramírez Barragán, A. Tatay Díaz, M. de los Llanos Rodríguez Rodríguez, J. Valdivieso García, I. Sanpera Trigueros, M. Vara Arias, J. Ruiz Sanz, E. Viosca Herrero, and L. de Sena de Cabo, *Parálisis cerebral infantil*, vol. 1. ERGON, 2015.

[33] E. Park, C. Park, and J. Kim, "Comparison of anterior and posterior walkers with respect to gait parameters and energy expenditure of children with spastic diplegic cerebral palsy," *Yonsei Medical Journal*, vol. 42, no. 2, pp. 180–4, 2001.

[34] C. Bache, P. Selber, and H. Graham, "The management of spastic diplegia," *Current Orthopaedics*, vol. 17, no. 2, pp. 88–104, 2003.

[35] A. Nene, G. Evans, and J. Patrick, "Simultaneous multiple operations for spastic diplegia. Outcome and functional assessment of walking in 18 patients," *The Bone and Joint Journal*, vol. 75, pp. 488–494, 1993.

[36] J. M. Rodda, H. K. Graham, G. R. Nattrass, M. P. Galea, R. Baker, and R. Wolfe, "Correction of severe crouch gait in patients with spastic diplegia with use of multilevel orthopaedic surgery.," *The Journal of bone and joint surgery. American volume*, vol. 88, pp. 2653–64, dec 2006.

[37] P. Thomason, R. Baker, K. Dodd, N. Taylor, P. Selber, R. Wolfe, and H. K. Graham, "Single-event multilevel surgery in children with spastic diplegia: a pilot randomized controlled trial.," *The Journal of bone and joint surgery. American volume*, vol. 93, pp. 451–60, mar 2011.

[38] K. Koka, C. Yildiz, Y. Yurttas, B. Balaban, B. Hazneci, S. Bilgiç, and M. Babozkurt, "Outcomes of multilevel orthopedic surgery in children with cerebral palsy," *Eklem Hastalik Cerrahisi*, vol. 22, no. 2, pp. 69–74, 2011.

[39] M. Gough, L. Eve, R. Robinson, and A. Shortland, "Short-term outcome of multilevel surgical intervention in spastic diplegic cerebral palsy compared with the natural history," *Developmental medicine and child neurology*, vol. 46, pp. 91–97, 2004.

[40] E. Zwick, V. Saraph, W. Strobl, and G. Steinwender, "Single event multilevel surgery to improve gait in diplegic cerebral palsy- a prospective controlled trial," *Z Orthop Ihre Grenzgeb*, vol. 139, no. 6, pp. 485–489, 2001.

[41] N. Thompson, J. Stebbins, M. Seniorou, A. Wainwright, D. Newham, and T. Theologis, "The use of minimally invasive techniques in multi-level surgery for children with cerebral palsy," *The Journal of bone and joint surgery (Br)*, vol. 92B, pp. 1442–8, 2010.

[42] S. E. Fasoli, B. Ladenheim, J. Mast, and H. I. Krebs, "New horizons for robot-assisted therapy in pediatrics.," *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*, vol. 91, pp. S280–9, nov 2012.

[43] S. Maggioni, A. Melendez-Calderon, E. van Asseldonk, V. Klamroth-Marganska, L. Lünenburger, R. Riener, and H. van der Kooij, "Robot-aided assessment of lower extremity functions: a review," *Journal of NeuroEngineering and Rehabilitation*, vol. 13, no. 1, p. 72, 2016.

[44] J. W. Yoo, D. R. Lee, Y. J. Sim, J. H. You, and C. J. Kim, "Effects of innovative virtual reality game and EMG biofeedback on neuromotor control in cerebral palsy.," *Bio-medical materials and engineering*, vol. 24, pp. 3613–8, jan 2014.

[45] G. G. Fluet, Q. Qiu, D. Kelly, H. D. Parikh, D. Ramirez, S. Saleh, and S. V. Adamovich, "Interfacing a haptic robotic system with complex virtual environments to treat impaired upper extremity motor function in children with cerebral palsy.," *Developmental neurorehabilitation*, vol. 13, pp. 335–45, jan 2010.

[46] T. Sukal-Moulton, T. Clancy, L.-Q. Zhang, and D. Gaebler-Spira, "Clinical application of a robotic ankle training program for cerebral palsy compared to the research laboratory application: does it translate to practice?," *Physical Medicine and Rehabilitation*, vol. 95, no. October 2013, pp. 1433–1440, 2014.

[47] D. Corbetta, F. Imeri, and R. Gatti, "Rehabilitation that incorporates virtual reality is more effective than standad rehabilitation for improving walking speed, balance and mobility after stroke: a systematic review," *Journal of Physiotherapy*, vol. 61, pp. 117–124, 2015.

[48] D. L. Damiano and S. L. DeJong, "A systematic review of the effectiveness of treadmill training and body weight support in pediatric rehabilitation.," *Journal of neurologic physical therapy : JNPT*, vol. 33, pp. 27–44, mar 2009.

[49] K. Willoughby, K. Dodd, and N. Shields, "A systematic review of the effectiveness of treadmill training for children with cerebral palsy," *Disability and rehabilitation*, 2009.

[50] H. Barbeau and M. Visintin, "Optimal outcomes obtained with body-weight support combined with treadmill training in stroke subjects," *Archives of physical medicine and rehabilitation*, vol. 84, pp. 1458–65, 2003.

[51] C. Ammann-Reiffer, C. Bastiaenen, A. Meyer-Heim, and H. van Hedel, "Effectiveness of robot-assisted gait training in children with cerebral palsy: a bicenter, pragmatic, randomized, cross-over trial (PeLoGAIT)," *BMC Pediatrics*, vol. 17, no. 1, p. 64, 2017.

[52] A. Frizera, R. Raya, J. Pons, A. Abellanas, and R. Ceres, "The smart walkers as geriatric assistive device," in *6th International Conference of the International Society for Gerontechnology*, 2008.

[53] S. Fasoli, M. Fragala-Pinkham, R. Hughes, and Etal, "Upper limb robotic therapy for children with hemiplegia," *American Journal of Physical Medicine and Rehabilitation*, vol. 87, no. 11, pp. 929–936, 2008.

[54] A. Waldner, "Robot Assisted Therapy in neurorehabilitation," *Europa Medicophysica*, vol. 44, pp. 1–3, 2008.

[55] Q. Qiu, D. Ramirez, S. Saleh, and E. Al, "Virtual Rehabilitation (NJIT-RAVR) system for children with cerebral palsy," *Journal of Neuroengineering and Rehabilitation*, no. 6, p. 40, 2009.

[56] R. Sanchez, J. Liu, and Raos, "Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity reduced environment," *IEEE Transactions on Neural Systems and Rehabilitation*, vol. 14, pp. 378–389, 2006.

[57] YouRehab Company, "Rehabilitación de YouGrabber para los miembros superiores - YouRehab - News y comunicados de prensa."

[58] YouRehab Company, "YouRehab (YouGrabber)."

[59] M. Gilliaux, A. Renders, D. Dispa, D. Holvoet, J. Sapin, B. Dehez, C. Detrembleur, T. M. Lejeune, and G. Stoquart, "Upper limb robot-assisted therapy in cerebral palsy: a single-blind randomized controlled trial.," *Neurorehabilitation and neural repair*, vol. 29, pp. 183–92, feb 2015.

[60] M. Gilliaux, T. M. Lejeune, C. Detrembleur, J. Sapin, B. Dehez, C. Selves, and G. Stoquart, "Using the robotic device REAplan as a valid, reliable, and sensitive tool to quantify upper limb impairments in stroke patients," *Journal of rehabilitation medicine*, vol. 46, no. 2, pp. 117–125, 2013.

[61] a. Meyer-Heim, C. Ammann-Reiffer, a. Schmartz, J. Schäfer, F. H. Sennhauser, F. Heinen, B. Knecht, E. Dabrowski, and I. Borggraefe, "Improvement of walking abilities after robotic-assisted locomotion training in children with cerebral palsy.," *Archives of disease in childhood*, vol. 94, pp. 615–20, aug 2009.

[62] A. M. Dollar and H. Herr, "Active Orthoses for the Lower-Limbs: Challenges and State of the Art," in *2007 IEEE 10th International Conference on Rehabilitation Robotics*, pp. 968–977, IEEE, jun 2007.

[63] A. Kangude, B. Burgstahler, J. Kakastys, and W. Durfee, "Single channel hybrid fes gait system using an energy storing orthosis: preliminary design," in *IEEE Engineering in Medicine & Biology Society*, pp. 6798–6801, 2009.

[64] M. H. Gharooni and S. Tokhi, "The use of elastic element in a hybrid orthosis for swing phase generation in orthotic gait," in *5 Annual Conf of the International Functional Electrical Stimulation Society*, 2000.

[65] R. J. Farris, H. A. Quintero, T. J. Withrow, and M. Goldfarb, "Design and simulation of a joint-coupled orthosis for regulating fes-aided gait

in robotics and automation," in *IEEE International Conference on DOI - 10.1109/ROBOT.2009.5152634*, pp. 1916–1922, 2009.

[66] W. Durfee and M. Goldfarb, "Design of a controlled-brake orthosis for regulating fes-aided gait," in *Annual International Conference of the IEE DOI*, pp. 1337–1338, 1992.

[67] D. Popovic, R. Tomovic, and L. Schwirtlich, "Hybrid assistive system-the motor neuroprosthesis," *Biomedical Engineering. IEEE Transactions on DOI - 10.1109/10.32105*, no. 36(7), pp. 729–737, 1989.

[68] G. Obinata, S. Fukada, T. Matsunaga, T. Iwami, Y. Shimada, K. Miyawaki, K. Hase, and A. Nakayama, "Hybrid control of powered orthosis and functional neuromuscular stimulation for restoring gait," in *IEEE Engineering in Medicine & Biology Society*, pp. 4879–4882, 2007.

[69] P. Al-Khodairy, A. Brodard, R. Fournier, J. Bouri, M. Clavel, R. Schmitt, and C. Metrailler, "A study of a knee extension controlled by a closed loop functional electrical stimulation," in *Annual Conf. of the International Functional Electrical Stimulation Society*, 2004.

[70] Y. Stauffer, Y. Allemand, M. Bouri, J. Fournier, R. Clavel, P. Metrailler, R. Brodard, and F. Reynard, "The walktrainer–a new generation of walking reeducation device combining orthoses and muscle stimulation," *IEEE Transactions on Neural Systems and Rehabilitation*, no. 17(1), pp. 38–45, 2009.

[71] H. I. Krebs, N. Hogan, M. L. Aisen, and B. Volpe, "Robot aided neurorehabilitation," *IEEE Transactions on Rehabilitation Engineering*, no. 6(1), pp. 75–87, 1998.

[72] Made for Movement, "NF-Walker — Made for Movement."

[73] Made for Movement, "Innowalk — Made for Movement."

[74] G. Colombo, M. Joerg, R. Schreier, and V. Dietz, "Treadmill training of paraplegic patients using a robotic orthosis.," *Journal of rehabilitation research and development*, vol. 37, no. 6, pp. 693–700, 2000.

[75] N. Smania, P. Bonetti, M. Gandolfi, A. Cosentino, A. Waldner, S. Hesse, C. Werner, G. Bisoffi, C. Geroin, and D. Munari, "Improved gait after repetitive locomotor training in children with cerebral palsy.," *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*, vol. 90, pp. 137–49, feb 2011.

[76] Walkbot, "Walkbot English."

[77] H. University, “Multi-Robot Cyber-Physical System For Assisting Young Developmentally-Delayed Children in Learning to Walk — CPS-VO.”

[78] N. Smania, M. Gandolfi, V. Marconi, A. Calanca, C. Geroin, S. Piazza, P. Bonetti, P. Fiorini, A. Consentino, C. Capelli, D. Conte, M. Bendinelli, D. Munari, P. Ianes, A. Fiaschi, and A. Picelli, “Applicability of a new robotic walking aid in a patient with cerebral palsy,” *Euro J Phys Rehabil Med*, vol. 47, no. 0, pp. 1–7, 2011.

[79] Made for Movement, “Innowalk Pro — Made for Movement.”

[80] Innowalk, “Experience from two counties in Norway,” 2009.

[81] A. Meyer, M. Kofler, E. Quirbach, H. Matzak, K. Fröhlich, and L. Saltuari, “Prospective, blinded, randomized crossover study of gait rehabilitation in stroke patients using the Lokomat gait orthosis.,” *Neurorehabilitation and neural repair*, vol. 21, no. 4, pp. 307–14, 2007.

[82] P. Verazaluce-Rodríguez, P. Rodríguez-Martínez, S. Neri-Gámez, and R. Hernández-Aquino, “Evolución de la marcha en pacientes con parálisis cerebral y desplazamiento asistido, mediante su entrenamiento con equipo de asistencia robótica,” *Rehabilitación*, vol. 48, pp. 3–8, jan 2014.

[83] I. Borggraefe, L. Kiwull, J. S. Schaefer, I. Koerte, A. Blaschek, A. Meyer-Heim, and F. Heinen, “Sustainability of motor performance after robotic-assisted treadmill therapy in children: an open, non-randomized baseline-treatment study.,” *European journal of physical and rehabilitation medicine*, vol. 46, pp. 125–31, jun 2010.

[84] E. H. F. van Asseldonk and H. van der Kooij, “Robot-Aided Gait Training with LOPES,” in *Neurorehabilitation Technology* (V. Dietz, ed.), pp. 379–396, London: Springer London, 2012.

[85] E. H. F. Van Asseldonk, J. F. Veneman, R. Ekkelenkamp, J. H. Buurke, F. C. T. Van Der Helm, and H. Van Der Kooij, “The effects on kinematics and muscle activity of walking in a robotic gait trainer during zero-force control,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 16, no. 4, pp. 360–370, 2008.

[86] M. Pirpiris, A. J. Wilkinson, J. Rodda, T. C. Nguyen, R. J. Baker, G. R. Nattrass, and H. K. Graham, “Walking speed in children and young adults with neuromuscular disease: comparison between two assessment methods.,” *Journal of pediatric orthopedics*, vol. 23, pp. 302–7, jan 2003.

[87] Z. Lerner, D. Damiano, H.-S. Park, A. Gravunder, and T. Bulea, "A Robotic Exoskeleton for Treatment of Crouch Gait in Children with Cerebral Palsy: Design and Initial Application," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, no. August 2008, pp. 1–1, 2016.

[88] L. Wallard, G. Dietrich, Y. Kerlirzin, and J. Bredin, "Robotic-assisted gait training improves walking abilities in diplegic children with cerebral palsy," *European Journal of Paediatric Neurology*, pp. 1–8, 2017.

[89] I. Borggraefe, A. Meyer-Heim, A. Kumar, J. S. Schaefer, S. Berweck, and F. Heinen, "Improved gait parameters after robotic-assisted locomotor treadmill therapy in a 6-year-old child with cerebral palsy," *Movement Disorders*, vol. 23, no. 2, pp. 280–283, 2008.

[90] I. Borggraefe, J. S. Schaefer, M. Klaiber, E. Dabrowski, C. Ammann-Reiffer, B. Knecht, S. Berweck, F. Heinen, and A. Meyer-Heim, "Robotic-assisted treadmill therapy improves walking and standing performance in children and adolescents with cerebral palsy," *European Journal of Paediatric Neurology*, vol. 14, no. 6, pp. 496–502, 2010.

[91] J. Meuleman, E. Van Asseldonk, G. Van Oort, H. Rietman, and H. Van Der Kooij, "LOPES II - Design and Evaluation of an Admittance Controlled Gait Training Robot with Shadow-Leg Approach," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 24, no. 3, pp. 352–363, 2016.

[92] O. Pinzone, M. Schwartz, P. Thomason, and R. Baker, "The comparison of normative reference data from different gait analysis services," *Gait & posture*, vol. 40, no. 2, pp. 286–290, 2014.

[93] N. Smania, M. Gandolfi, V. Marconi, A. Calanca, C. Geroin, S. Piazza, P. Bonetti, P. Fiorini, A. Cosentino, C. Capelli, D. Conte, M. Bendinelli, D. Munari, P. Ianes, A. Fiaschi, and A. Picelli, "Applicability of a new robotic walking aid in a patient with cerebral palsy. Case report.," *European journal of physical and rehabilitation medicine*, vol. 48, pp. 147–53, mar 2012.

[94] K. Dodd and S. Foley, "Partial body-weight-supported treadmill training can improve walking in children with cerebral palsy: A clinical controlled trial," *Developmental Medicine and Child Neurology*, vol. 49, pp. 101–105, 2007.

[95] B. H. Dobkin and P. W. Duncan, "Should body weight–supported treadmill training and robotic-assistive steppers for locomotor training trot back to the starting gate?," *Neurorehabilitation and Neural Repair*, vol. 26, pp. 308–317, 2012.

[96] R. Dewar, S. Love, and L. M. Johnston, "Exercise interventions improve postural control in children with cerebral palsy: a systematic review.," *Developmental medicine and child neurology*, dec 2014.

[97] E. Abd El-Kafy and H. El-Basatini, "Effect of postural balance training on gait parameters in children with cerebral palsy.," *American Journal of Physical Medicine and Rehabilitation*, vol. 93, no. 11, pp. 938–947, 2014.

[98] N. Bayona, J. Bitensky, K. Salter, and R. Teasell, "The role of task-specific training in rehabilitation therapies," *Top Stroke Rehabil.*, vol. 12, no. 3, pp. 58–65, 2005.

[99] C. Bayón, O. Ramírez, M. D. del Castillo, J. Serrano, R. Raya, J. Belda-Lois, R. Poveda, F. Mollà, T. Martín, I. Martínez-Caballero, S. Lerma Lara, and E. Rocon, "CPWalker: Robotic Platform for Gait Rehabilitation in Patients with Cerebral Palsy," in *IEEE International Conference on Robotics and Automation*, 2016.

[100] A. Cullell, J. C. Moreno, E. Rocon, A. Forner-Cordero, and J. L. Pons, "Biologically based design of an actuator system for a knee-ankle-foot orthosis," *Mech. Mach.Theory*, vol. 44, no. 4, pp. 860–872, 2009.

[101] M. R. Tucker, J. Olivier, A. Pagel, H. Bleuler, M. Bouri, and O. Lambercy, "Control strategies for active lower extremity prosthetics and orthotics : a review Control strategies for active lower extremity prosthetics and orthotics : a review," *Journal of Neuroengineering and Rehabilitation*, vol. 12, no. 1, pp. 1–29, 2015.

[102] M. Spenko, H. Yu, and S. Dubowsky, "Robotic personal aids for mobility and monitoring for the elderly," *IEEE Transactions on Neural Systems and Rehabilitation*, no. 14(3), pp. 344–351, 2006.

[103] D. Rodriguez-losada, F. Matia, R. Galan, G. Lacey, and A. Jiménez, "Implementing Map Based Navigation in Guido , the robotic smart walker," *IEEE International Conference on Robotics and Automation*, no. April, pp. 3401–3406, 2005.

[104] A. Frizera, R. Ceres, E. Rocon, and J. Pons, "Empowering and assisting natural human mobility: The Simbiosis Walker," *Intl. J. Adv. Robot. Syst.*, vol. 8, no. 3, pp. 34–50, 2011.

[105] H. Munawar, M. Yalcin, and V. Patoglu, "Redundant Kinematics and Workspace Centering Control of AssistOn-Gait Overground Gait and Balance Trainer," in *IEEE International Conference on Robotics and Automation (ICRA)*, pp. 3704–3710, 2016.

[106] Kelvin, "Catálogo Kelvin motores y reductores."

[107] H. van der Kooij, B. Koopman, and E. H. F. van Asseldonk, "Body weight support by virtual model control of an impedance controlled exoskeleton (LOPES) for gait training.," *Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, vol. 2008, pp. 1969–1972, 2008.

[108] SKF, "SKF-Linear actuator."

[109] Bansbach, "Bansbach Linear actuator system."

[110] G. Aguirre-Ollinger, "Exoskeleton control for lower-extremity assistance based on adaptive frequency oscillators: Adaptation of muscle activation and movement frequency," *Journal of Engineering in Medicine*, vol. 229, no. 1, pp. 52–68, 2015.

[111] R. Riener, L. Lünenburger, S. Jezernik, M. Anderschiz, G. Colombo, and V. Dietz, "Patient-Cooperative Strategies for Robot-Aided Treadmill Training : First Experimental Results," *Transactions on neural systems and rehabilitacion engineering*, vol. 13, no. 3, pp. 380–394, 2005.

[112] V. Bartenbach, M. Gort, and R. Riener, "Concept and Design of a Modular Lower Limb Exoskeleton," in *6th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, pp. 649–654, 2016.

[113] Harmonic Drive gear, "Cup Type Component Sets & Housed Units."

[114] Maxon Motor, "Maxon Motor product 408057."

[115] A. Lauletta, "The Basics of Harmonic Drive Gearing," 2006.

[116] E. Rocon, J. M. Belda-Lois, A. F. Ruiz, M. Manto, J. C. Moreno, and J. L. Pons, "Design and validation of a rehabilitation robotic exoskeleton for tremor assessment and suppression," *IEEE transactions on neural systems and rehabilitation engineering*, vol. 15, pp. 367–378, sep 2007.

[117] G. Colombo, M. Joerg, R. Schreier, and V. Dietz, "Treadmill training of paraplegic patients using a robotic orthosis.," *Journal of rehabilitation research and development*, vol. 37, no. 6, pp. 693–700, 2000.

[118] J. Doke, J. M. Donelan, and A. D. Kuo, "Mechanics and energetics of swinging the human leg.," *The Journal of experimental biology*, vol. 208, no. Pt 3, pp. 439–445, 2005.

[119] Vishay, "Precision Potentiometers Industrial Sensors."

[120] E. Rocon, *Reducción activa de temblor patológico de miembro superior mediante exoesqueletos robóticos.* PhD thesis, Universidad Politécnica de Madrid, 2006.

[121] M. Bortole, A. Venkatakrishnan, F. Zhu, J. C. Moreno, G. E. Francisco, J. L. Pons, and J. L. Contreras-Vidal, "The H2 robotic exoskeleton for gait rehabilitation after stroke: early findings from a clinical study," *Journal of NeuroEngineering and Rehabilitation*, vol. 12, no. 1, p. 54, 2015.

[122] Wikipedia, "CAN Bus," 2016.

[123] M. Bortole, *Robotic Exoskeleton with an assist-as-needed control strategy for gait rehabilitation after stroke.* PhD thesis, Universidad Carlos III, 2014.

[124] Wikipedia, "PC104."

[125] Diamond System Corporation, "Diamond-MM-32-AT PC/104."

[126] MathWorks, "Simulink Coder - Real-Time Workshop - MathWorks España," 2015.

[127] M. Bax, C. Tydeman, and O. Flodmark, "Clinical and MRI correlates of cerebral palsy: the European Cerebral Palsy Study," *Jama*, vol. 296, no. 13, pp. 1602–1608, 2006.

[128] E. G. Fowler, L. A. Staudt, M. B. Greenberg, and W. L. Oppenheim, "Selective Control Assessment of the Lower Extremity (SCALE): Development, validation, and interrater reliability of a clinical tool for patients with cerebral palsy," *Developmental Medicine and Child Neurology*, vol. 51, no. 8, pp. 607–614, 2009.

[129] F. Galán, M. Nuttin, E. Lew, P. Ferrez, G. Vanacker, J. Philips, and J. d. R. Millán, "A Brain-Actuated Wheelchair: Asynchronous and Non-Invasive Brain-Computer Interfaces for Continuous Control of Robots," *Clinical Neurophysiology*, vol. 119, pp. 2159–2169, 2008.

[130] C. Neuper, G. Müller, A. Kübler, N. Birbaumer, and G. Pfurtscheller, "Clinical application of an EEG-based brain–computer interface: a case study in a patient with severe motor impairment.," *Clinical Neurophysiology*, vol. 114, pp. 339–409, 2002.

[131] C. Neuper, G. Müller, R. Scherer, and G. Pfurtscheller, "Motor imagery and EEG-based control of spelling devices and neuroprostheses.," in *Progress in Brain Research* (C. Neuper and Klimesch, eds.), -, 159 ed., 2006.

[132] G. Pfurtscheller, G. Müller, J. Pfurtscheller, H. Gernerd, and R. Rupp, "Thought' – control of functional electrical stimulation to restore hand grasp in a patient with tetraplegia," *Neuroscience Letters*, vol. 351, pp. 33–36, 2003.

[133] G. Müller, R. Scherer, G. Pfurtscheller, and R. Rupp, "EEG-based neuroprosthesis control: A step towards clinical practice," *Neuroscience Letters*, vol. 382, pp. 169–174, 2005.

[134] G. Pfurtscheller, G. Müller, and C. Neuper, “Rehabilitation with Brain-Computer Interface Systems.,” in *Computer, IEEE*, 2008.

[135] G. Pfurtscheller, G. Müller, J. Pfurtscheller, H. Gernerd, and R. Rupp, “Thought-control of functional electric stimulation to restore hand grasp in a patient with tetraplegia.,” *Neuroscience Letters*, vol. 382, pp. 169–174, 2003.

[136] M. Lebedev and M. Nicolelis, “Brain-machine interfaces: past, present and future.,” *Trends in Neurosciences*, vol. 29, no. 9, pp. 536–546, 2006.

[137] D. Farina, K. Yoshida, T. Stieglitz, and K. Koch, “Multichannel thin-film electrode for intramuscular electromyographic recordings,” *Journal of Applied Physiology*, vol. 104, no. 3, pp. 821–827, 2008.

[138] J.-M. Belda-Lois, S. Mena-del Horno, I. Bermejo-Bosch, J. C. Moreno, J. L. Pons, D. Farina, M. Iosa, M. Molinari, F. Tamburella, A. Ramos, A. Caria, T. Solis-Escalante, C. Brunner, and M. Rea, “Rehabilitation of gait after stroke: a review towards a top-down approach.,” *Journal of neuroengineering and rehabilitation*, vol. 8, p. 66, jan 2011.

[139] Hooper and L. Scott, “Central Pattern Generators,” in *Encyclopedia of Life Sciences* (J. Wiley and Sons, eds.), Encyclopedia of Life Sciences, 2001.

[140] B. Calancie, B. Needham-Shropshire, P. Jacobs, K. Willer, G. Zych, and B. Green, “Involuntary stepping after chronic spinal cord injury. Evidence for a central rhythm generator for locomotion in man,” *Brain*, vol. 117, pp. 1143–59, 1994.

[141] D. Winter, *Biomechanics and Motor Control of Human Movement.* Wiley, John Sons, 2005.

[142] E. G. Fowler, L. A. Staudt, and M. B. Greenberg, “Lower-extremity selective voluntary motor control in patients with spastic cerebral palsy : increased distal motor impairment,” *Developmental Medicine & Child Neurology*, vol. 52, pp. 264–269, 2010.

[143] M. H. Schwartz, A. Rozumalski, and K. M. Steele, “Dynamic motor control is associated with treatment outcomes for children with cerebral palsy,” *Developmental Medicine and Child Neurology*, pp. 1–7, 2016.

[144] J. I. Serrano, M. D. Castillo, C. Bayón, O. Ramírez, S. Lerma, and E. Rocon, “BCI-based facilitation of cortical activity associated to gait onset after single event multi-level surgery in cerebral palsy,” in *Brain-Computer Interface Research: A state of the art Sumary 5*, pp. 99–110, Springer, 2017.

[145] C. A. Cifuentes, C. Bayon, S. Lerma, A. Frizera, and E. Rocon, "Human-Robot Interaction Strategy for Overground Rehabilitation in Patients with Cerebral Palsy," in *IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, pp. 729–734, 2016.

[146] S. Hussain, S. Q. Xie, and G. Liu, "Robot assisted treadmill training : Mechanisms and training strategies," *Medical Engineering and Physics*, vol. 33, no. 5, pp. 527–533, 2011.

[147] S. Jezernik, G. Colombo, and M. Morari, "Automatic Gait-Pattern Adaptation Algorithms for Rehabilitation With a 4-DOF Robotic Orthosis," *IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION*, vol. 20, no. 3, pp. 574–582, 2004.

[148] N. Smania, P. Bonetti, M. Gandolfi, A. Cosentino, A. Waldner, S. Hesse, C. Werner, G. Bisoffi, C. Geroin, and D. Munari, "Improved gait after repetitive locomotor training in children with cerebral palsy.," *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*, vol. 90, pp. 137–49, feb 2011.

[149] B. Husemann, F. Muller, C. Krewer, S. Heller, and E. Koenig, "Effects of locomotion training with assistance of a robot-driven gait orthosis in hemiparetic patients after stroke: A randomized controlled pilot study," *Stroke2*, vol. 38, pp. 349–354, 7.

[150] M. Pohl, C. Werner, M. Holzgraefe, G. Kroczck, J. Mehrholz, I. Wingendorf, G. Hoolig, R. Koch, and S. Hesse, "Repetitive Locomotor Training and physiotherapy improve walking and basic activities of daily living after stroke: a single-blind, randomized multicentre trial," *Clinical Rehabilitation*, vol. 21, pp. 17–27, 2007.

[151] B. Koopman, E. H. F. van Asseldonk, and H. Van der Kooij, "Speed-dependent reference joint trajectory generation for robotic gait support," *Journal of Biomechanics*, vol. 47, no. 6, pp. 1447–1458, 2014.

[152] N. Hogan, "Impedance Control: An Approach to Manipulation: parts I, II and III," *Journal of dynamic systems, measurement and control*, vol. 107, 1985.

[153] B. Koopman, E. H. F. V. Asseldonk, and H. V. D. Kooij, "Estimation of human hip and knee multi-joint dynamics using the lopes gait trainer," *IEEE Transactions on Robotics*, vol. 32, no. 4, pp. 920–932, 2016.

[154] S. Zhang, H. Yang, and L. Singh, "Rehabilitation Robotics: Performance-Based Progressive Robot-Assisted Therapy," *Autonomous Robots*, vol. 15, pp. 7–20, 2003.

[155] B. Koopman, E. H. F. van Asseldonk, and H. van der Kooij, "Selective control of gait subtasks in robotic gait training: foot clearance support in stroke survivors with a powered exoskeleton.," *Journal of neuroengineering and rehabilitation*, vol. 10, no. 1, p. 3, 2013.

[156] A. Kaelin-Lang, L. Sawaki, and L. Cohen, "Role of voluntary drive in encoding an elementary motor memory," *Journal of neurophysiology*, vol. 93, pp. 1099–1103, 2005.

[157] H. Taheri, D. J. Reinkensmeyer, and E. T. Wolbrecht, "Model-Based Assistance-as-Needed for Robotic Movement Therapy after Stroke," in *IEEE Engineering in Medicine & Biology Society*, pp. 2124–2127, 2016.

[158] A. Duschau-Wicke, J. von Zitzewitz, A. Caprez, L. Lunenburger, and R. Riener, "Path control: a method for patient-cooperative robot-aided gait rehabilitation.," *IEEE transactions on neural systems and rehabilitation engineering*, vol. 18, pp. 38–48, feb 2010.

[159] M. T. Robert, R. Guberek, H. Sveistrup, and M. F. Levin, "Motor learning in children with hemiplegic cerebral palsy and the role of sensation in short-term motor training of goal-directed reaching," *Developmental Medicine and Child Neurology*, vol. 55, no. 12, pp. 1121–1128, 2013.

[160] L. Heyrman, H. Feys, G. Molenaers, E. Jaspers, D. Monari, A. Nieuwenhuys, and K. Desloovere, "Altered trunk movements during gait in children with spastic diplegia: Compensatory or underlying trunk control deficit?," *Research in Developmental Disabilities*, vol. 35, no. 9, pp. 2044–2052, 2014.

[161] R. Raya, *Nuevas estrategias para la interacción y la movilidad de niños con parálisis cerebral según un modelo convergente.* PhD thesis, Universidad de Alcalá, 2011.

[162] D. J. Reinkensmeyer, E. Burdet, M. Casadio, J. W. Krakauer, G. Kwakkel, C. E. Lang, S. P. Swinnen, N. S. Ward, and N. Schweighofer, "Computational neurorehabilitation: modeling plasticity and learning to predict recovery," *Journal of NeuroEngineering and Rehabilitation*, pp. 1–25, 2016.

[163] C. Bayón, S. Fricke, E. Rocon, H. V. D. Kooij, and E. V. Asseldonk, "PERFORMANCE-BASED ADAPTIVE ASSISTANCE FOR DIFFERENT SUBTASKS OF WALKING IN LOPES II," in *Annual Symposium of the IEEE EMBS Benelux Chapter*, 2017.

[164] K. van Kammen, A. M. Boonstra, L. H. van der Woude, H. A. Reinders-Messelink, and R. den Otter, "The combined effects of guidance force, bodyweight support

and gait speed on muscle activity during able-bodied walking in the Lokomat," *Clinical Biomechanics*, vol. 36, pp. 65–73, jul 2016.

[165] H. J. A. van Hedel, L. Tomatis, and R. Müller, "Modulation of leg muscle activity and gait kinematics by walking speed and bodyweight unloading," *Gait and Posture*, vol. 24, no. 1, pp. 35–45, 2006.

[166] V. Dietz, "Clinical Aspects for the Application of Robotics in Locomotor Neurorehabilitation," in *Neurorehabilitation Technology* (D. J. Reinkensmeyer and V. Dietz, eds.), pp. 209–221, Springer, 2016.

[167] I. Diaz, J. Gil, and E. Sanchez, "Lower-limb Robotic Rehabilitation: literature review and challenges," *J Robot.*, 2011.

[168] S. Rüdt, M. Moos, S. Seppey, R. Riener, and L. Marchal-Crespo, "Towards More Efficient Robotic Gait Training: A Novel Controller to Modulate Movement Errors," *6th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics.*, pp. 884–889, 2016.

[169] C. Faigenbaum, Avery D. Kramer, W. Blimkie, "Youth Resistance Training: updated position statement paper from the National Strength and Conditioning Association," *J Strength Con Res*, vol. 23, no. 5, pp. 60–79, 2009.

[170] D. L. Damiano, M. F. Abel, A. D. Dl, and A. Mf, "Functional outcomes for strenght training in spastic cerebral palsy," *Archives of Physical Medicine and Rehabilitation*, vol. 79, no. February, pp. 119–125, 1998.

[171] T. Martín-Lorenzo, S. Lerma-Lara, C. Bayón, Ó. Ramírez, and E. Rocon, "The CPWalker for Strength Training in Children with Spastic Cerebral Palsy: A training program proposal," in *International Conference on Neurorehabilitation*, 2016.

[172] P. Rosenbaum and J. W. Gorter, "The "F-words" in childhood disability: I swear this is how we should think!," *Child: Care, Health and Development*, vol. 38, pp. 457–463, jul 2012.

[173] N. Maclean and P. Pound, "A critical review of the concept of patient motivation in the literature on physical rehabilitation.," *Social science & medicine (1982)*, vol. 50, pp. 495–506, feb 2000.

[174] Rehabilitation Measures Database, "Timed 10-Meter Walk Test."

[175] R. O. Crapo, R. Casaburi, A. L. Coates, P. L. Enright, N. R. MacIntyre, R. T. McKay, D. Johnson, J. S. Wanger, R. J. Zeballos, V. Bittner, and C. Mottram, "ATS statement: Guidelines for the six-minute walk test," *American Journal of Respiratory and Critical Care Medicine*, vol. 166, no. 1, pp. 111–117, 2002.

[176] G. Borg, "Psychophysical bases of perceived exertion," *Med. Science Sports Exerc.*, vol. 14, no. 5, pp. 377–81, 1982.

[177] P. Butler, M. Engelbrecht, R. E. Major, J. H. Tait, J. Stallard, and J. H. Patrick, "Physiological Cost Index of Walking for Normal Children and Its Use As an Indicator of Physical Handicap," *Developmental Medicine & Child Neurology*, vol. 26, no. 5, pp. 607–612, 1984.

[178] M. Kadaba, H. Ramakrishnan, and M. Wootten, "Measurement of Lower Extremity Kinematics During Level Walking," *Journal of Orthopaedic Research*, vol. 8, pp. 383–392, 1990.

[179] D. J. Russell, P. L. Rosenbaum, L. M. Avery, and M. Lane, *Gross motor function measure (GMFM-66 and GMFM-88) user's manual*. Press, Cambridge University, 2002.

[180] G. E. Gorton, J. L. Stout, A. M. Bagley, K. Bevans, T. F. Novacheck, and C. A. Tucker, "Gillette Functional Assessment Questionnaire 22-item skill set: Factor and Rasch analyses," *Developmental Medicine and Child Neurology*, vol. 53, no. 3, pp. 250–255, 2011.

[181] E. Y. Park and W. H. Kim, "Meta-analysis of the effect of strengthening interventions in individuals with cerebral palsy," *Research in Developmental Disabilities*, vol. 35, no. 2, pp. 239–249, 2014.

[182] T. Aurich-Schuler, F. Grob, H. Van Hedel, and R. Labruyère, "Can Lokomat therapy with children and adolescents be improved? An adaptive clinical pilot trial comparing Guidance force, Path control, and FreeD," *Journal of NeuroEngineering and Rehabilitation*, vol. 14, no. 1, pp. 1–14, 2017.

[183] J. Meuleman, *Design of a Robot-Assisted Gait Trainer*. PhD thesis, University of Twente, 2015.

[184] Stroke Engine, "Depth Review of the Functional Ambulation Categories (FAC)."

[185] H. Barbeau, M. Ladouceur, M. M. Mirbagheri, and R. E. Kearney, "The effect of locomotor training combined with functional electrical stimulation in chronic spinal cord injured subjects: walking and reflex studies," *Brain Res Brain Res Rev*, vol. 40, pp. 274–91, 2002.

[186] A. A. Abdel-aziem and H. M. El-Basatiny, "Effectiveness of backward walking training on walking ability in children with hemiparetic cerebral palsy: A randomized controlled trial," *Clinical Rehabilitation*, 2016.

[187] H. M. Y. El-Basatiny and A. A. Abdel-Aziem, "Effect of backward walking training on postural balance in children with hemiparetic cerebral palsy: a randomized controlled study.," *Clinical rehabilitation*, vol. 29, no. 5, pp. 457–67, 2015.

[188] W.-H. Kim, W.-B. Kim, and C.-K. Yun, "The effects of forward and backward walking according to treadmill inclination in children with cerebral palsy.," *Journal of physical therapy science*, vol. 28, no. 5, pp. 1569–73, 2016.